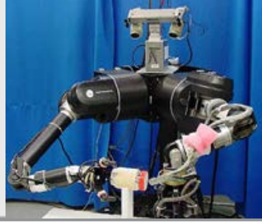
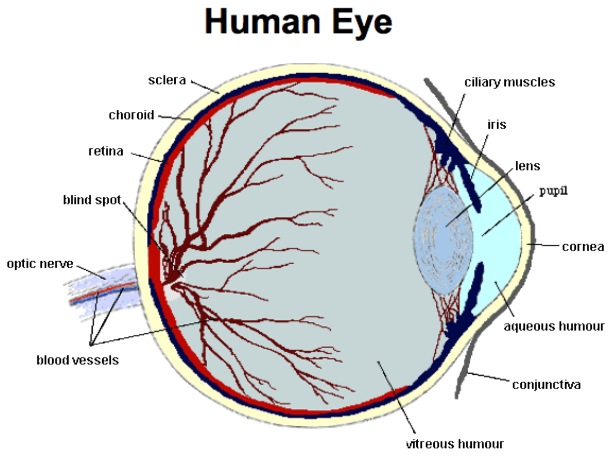
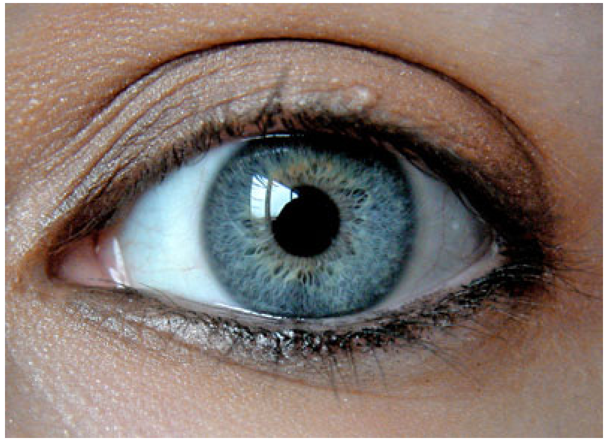
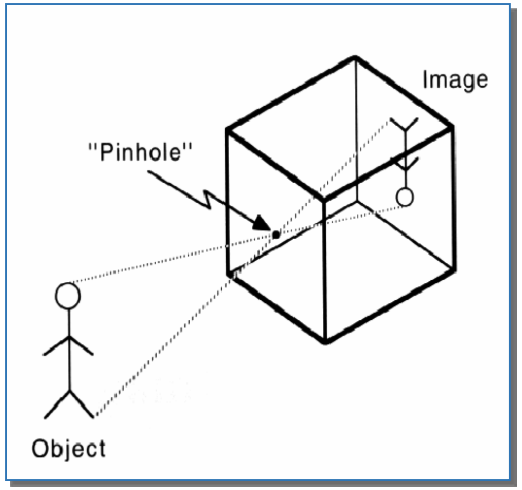
EVC - Computer Vision - Unit 16: Image Acquisition

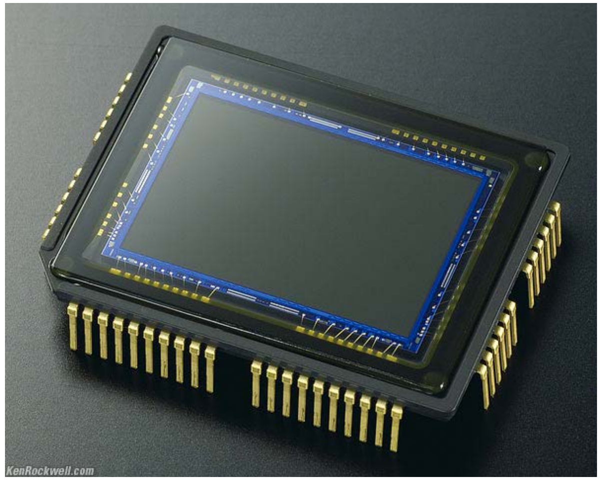


- Content:
  - Human Eye
  - Image Geometry
  - Lenses
  - Radiometry
  - Resolution/Sampling
  - Image Sensors
  - Cameras
  - Color



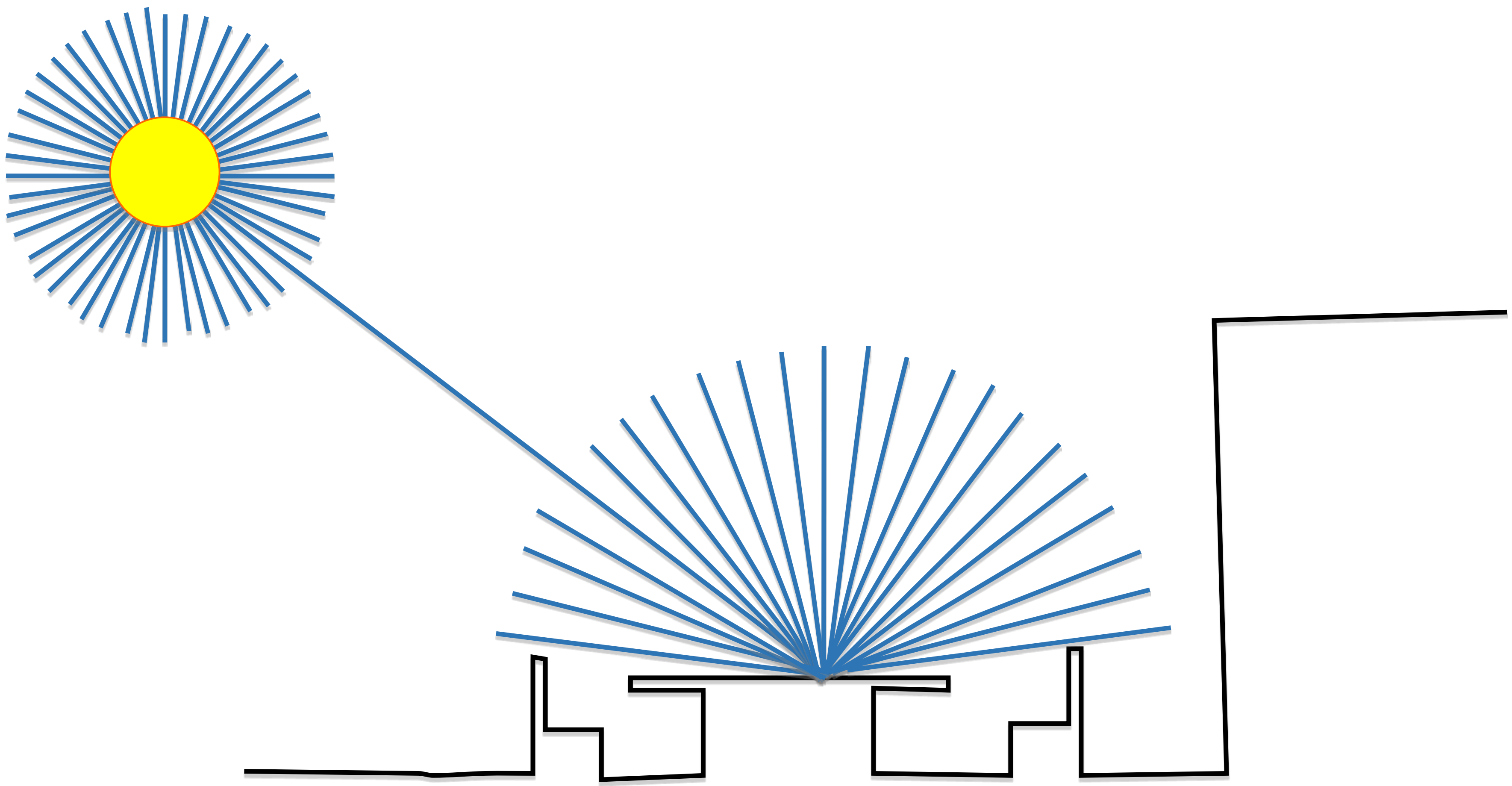




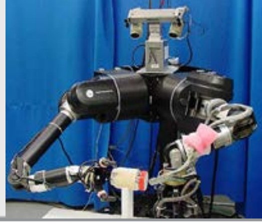


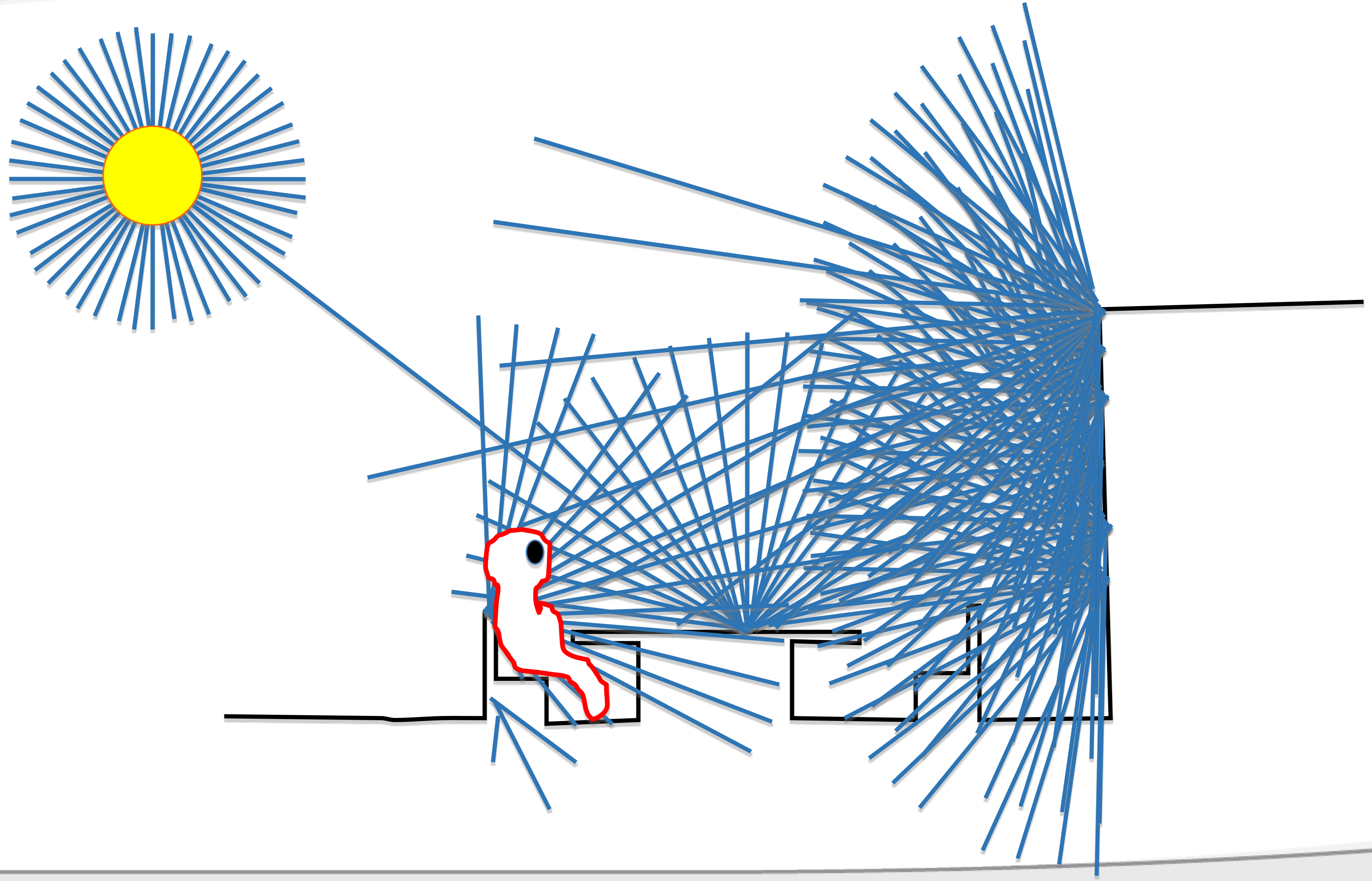
Why is Vision hard – The Plenoptic Function

The Structure of Ambient Light

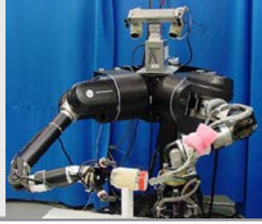


The Structure of Ambient Light



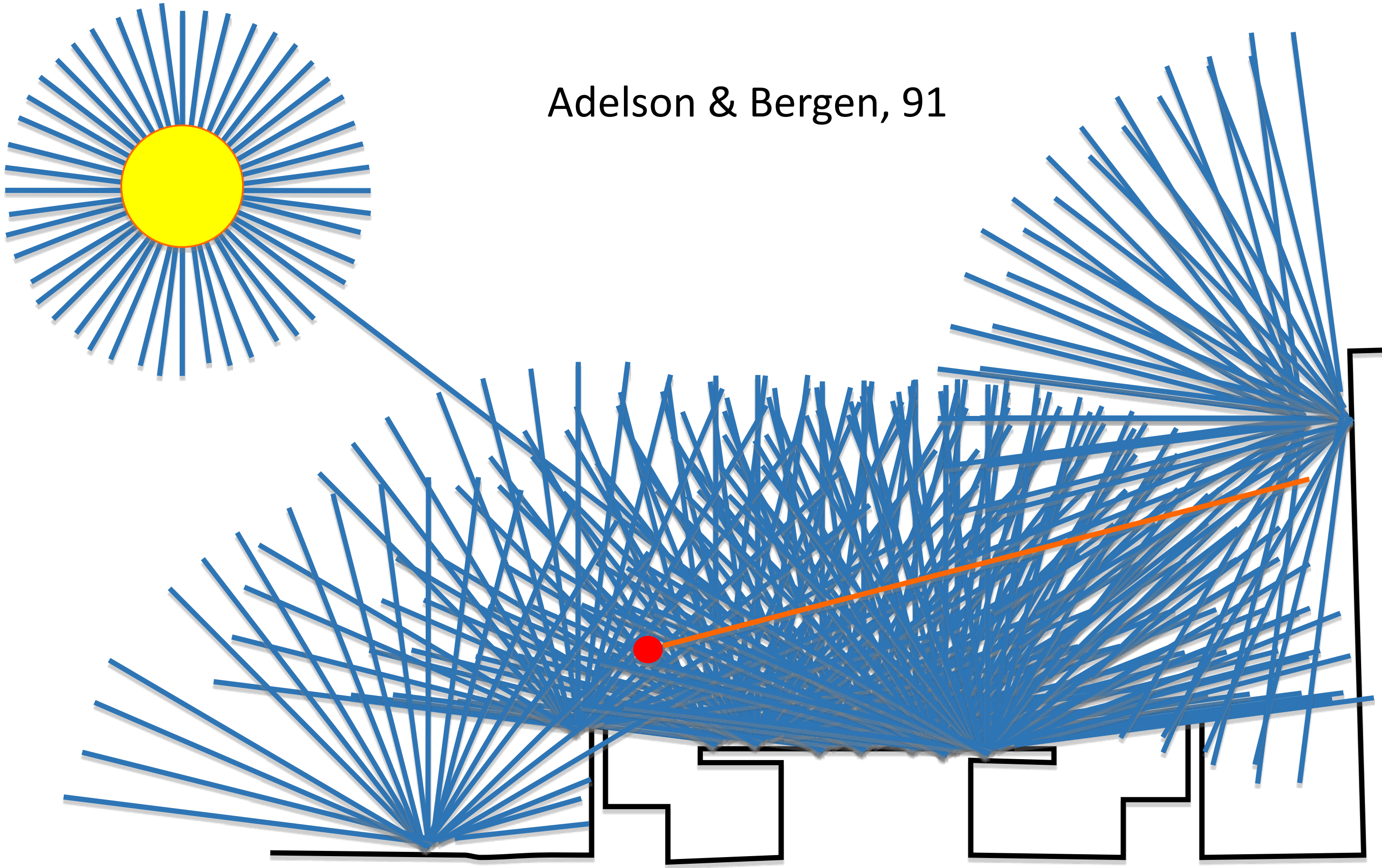


The Plenoptic Function



The intensity P can be parameterized as:

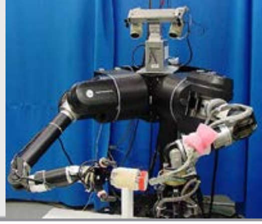
Adelson & Bergen, 91



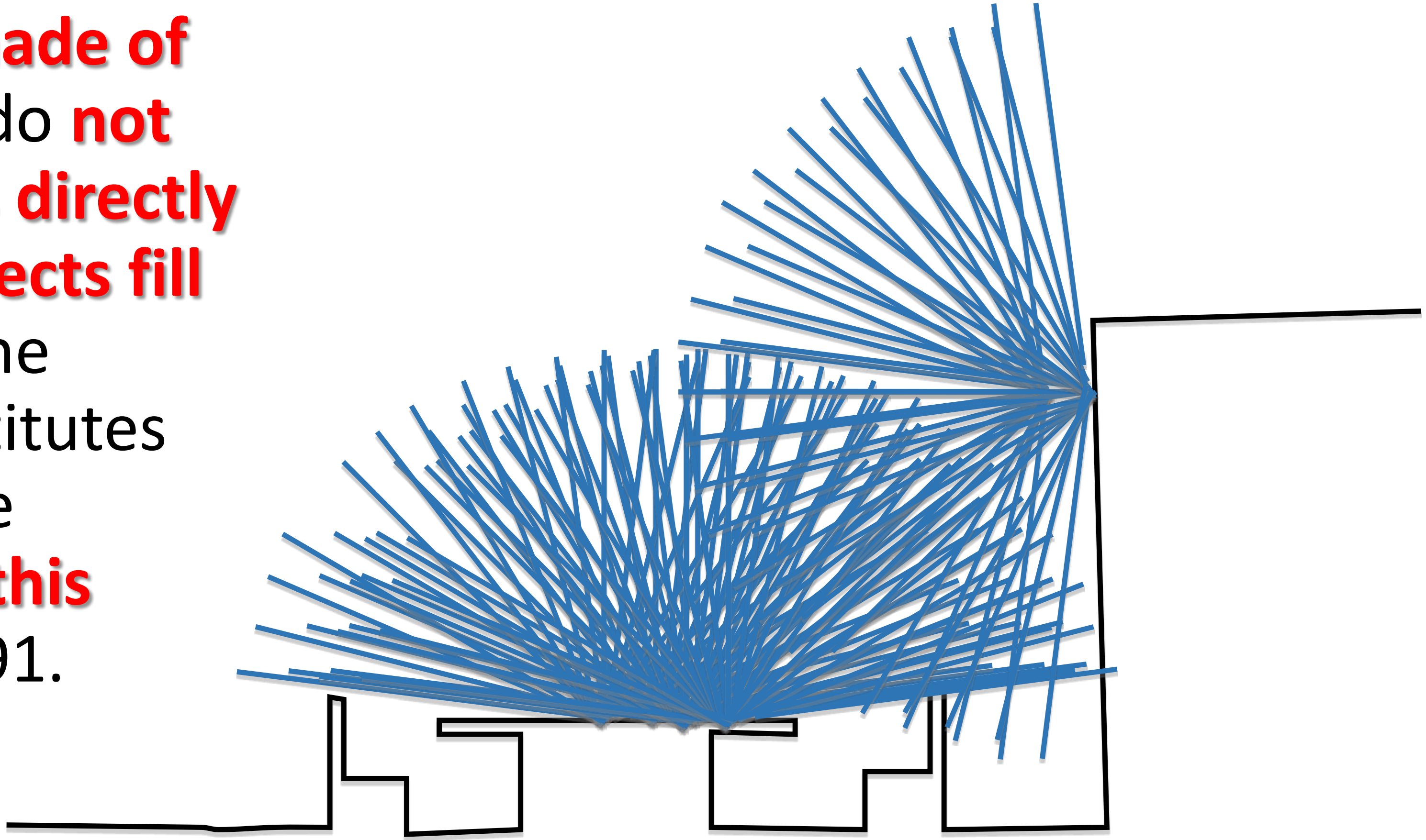
$$P(\theta, \phi, \lambda, t, X, Y, Z)$$

"The complete set of all convergence points constitutes the permanent possibilities of vision." Gibson

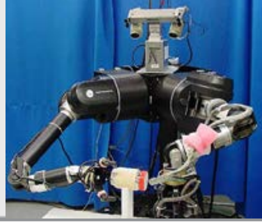
Measuring the Plenoptic Function

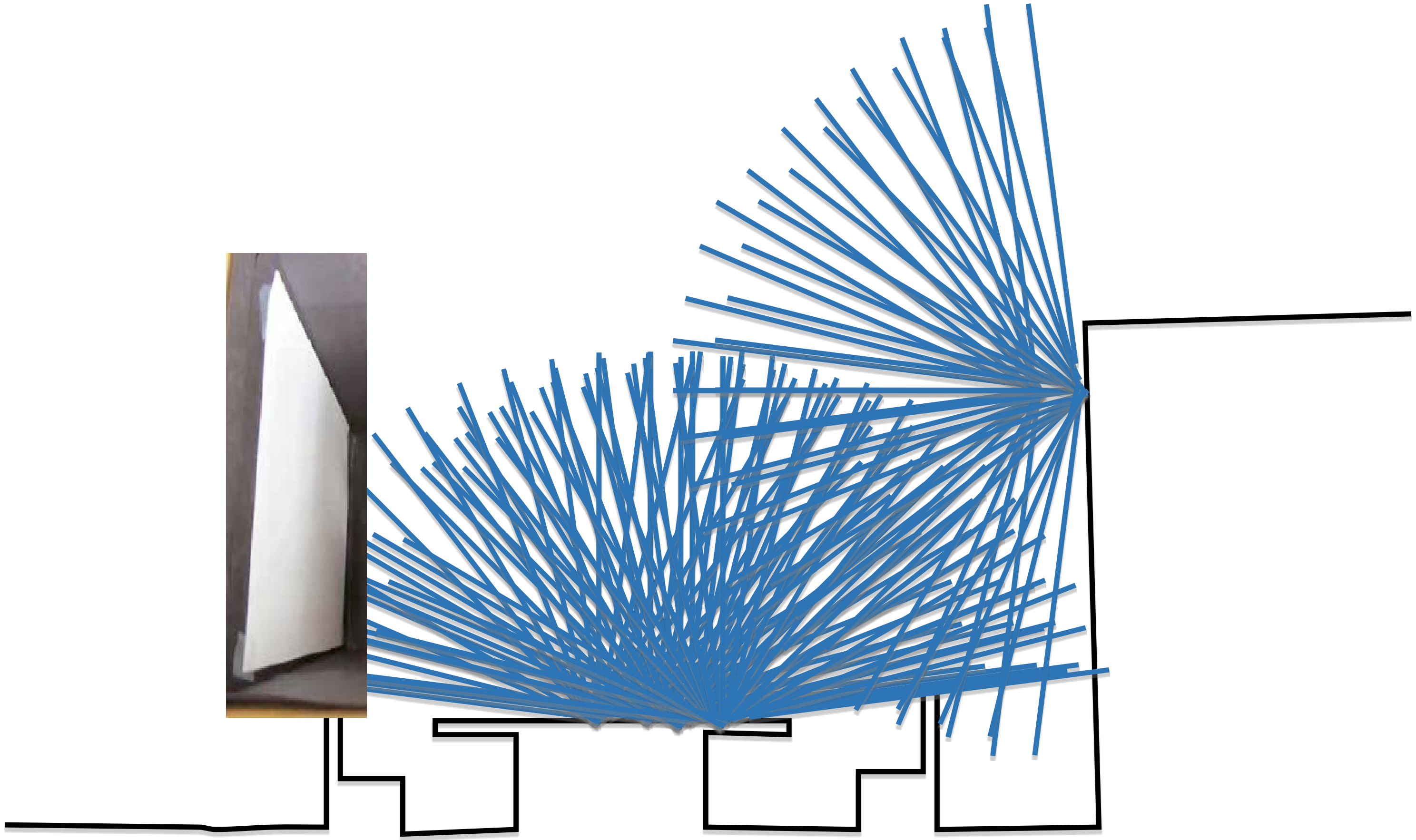


“The **significance** of the plenoptic function is this: The world is **made of 3D objects**, but these objects do **not communicate their properties directly** to an observer. Rather, the **objects fill the space** around them with the **pattern of light rays** that constitutes the plenoptic function, and the **observer takes samples from this function**.” Adelson, & Bergen 91.



Measuring the Plenoptic Function

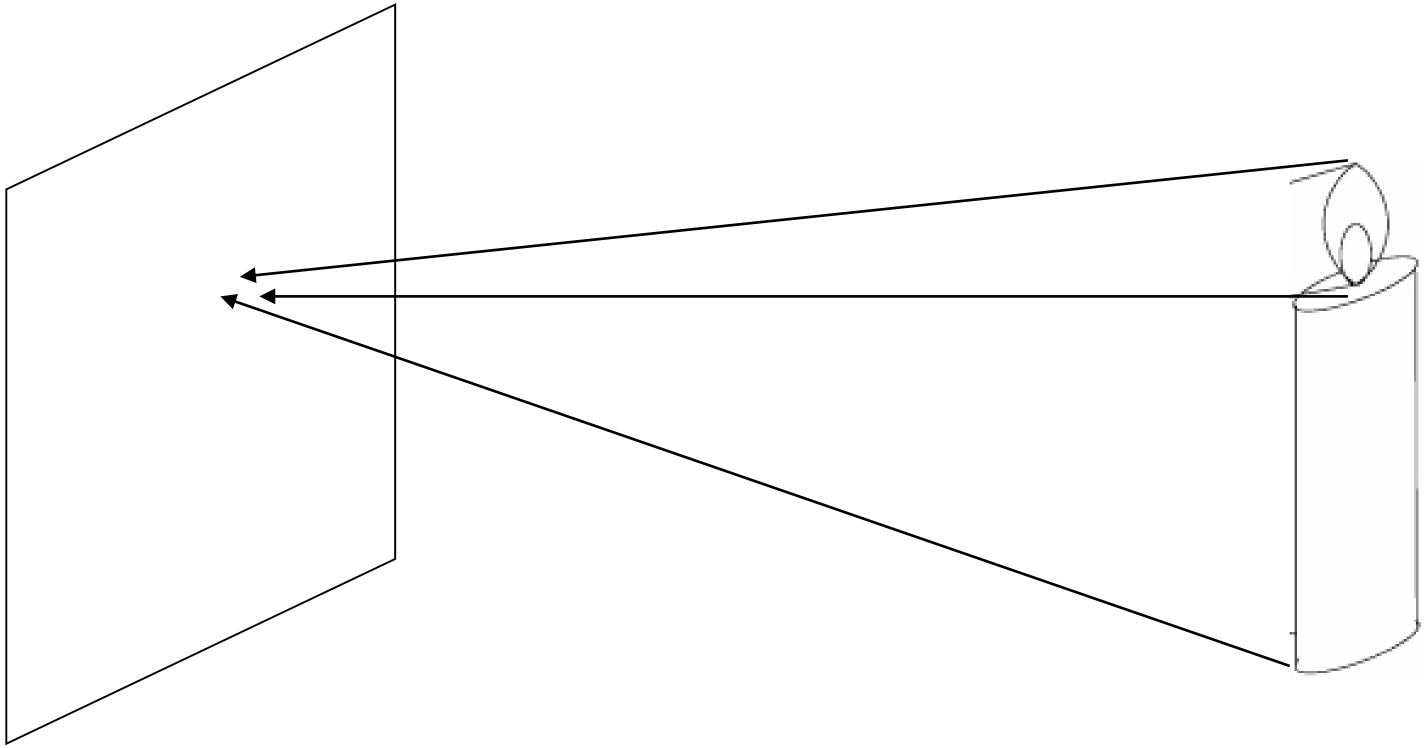




Why is there no picture appearing on the paper?

Measuring the Plenoptic Function

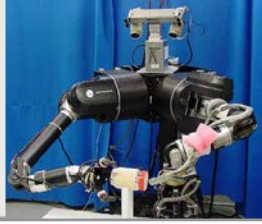
- Light rays from many different parts of the scene strike the same point on the paper.



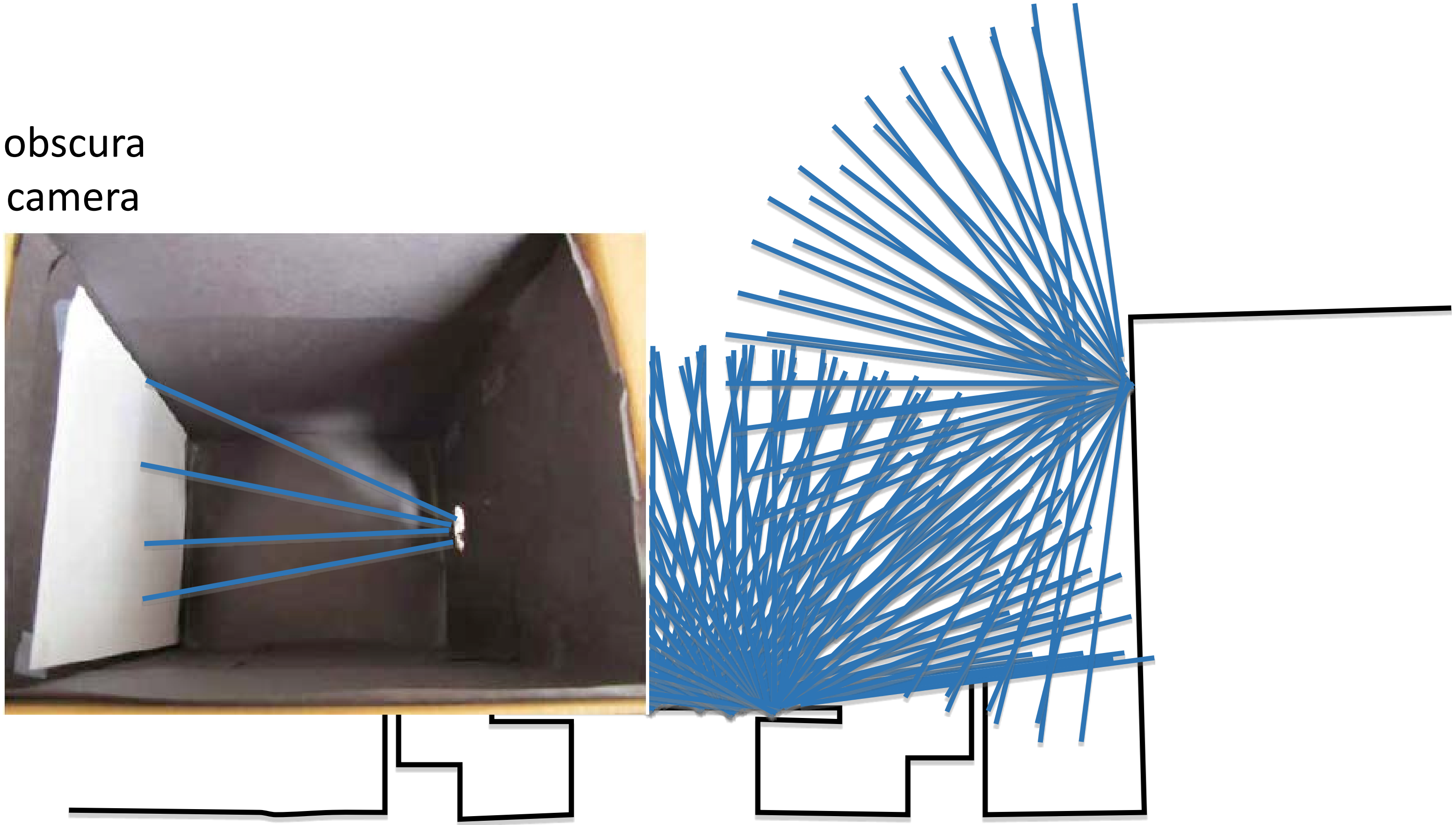
Forsyth & Ponce

Camera Obscura

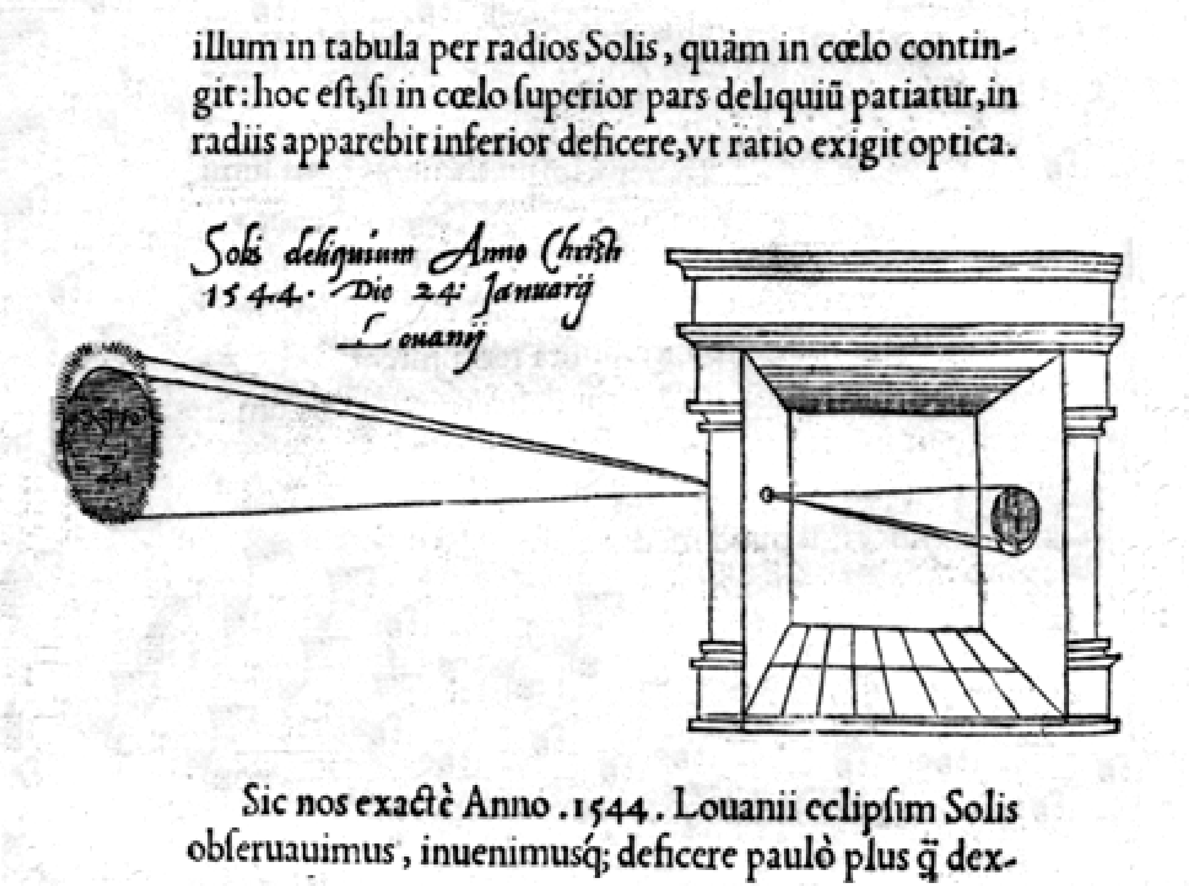
Measuring the Plenoptic Function



The camera obscura
The pinhole camera



Camera Obscura

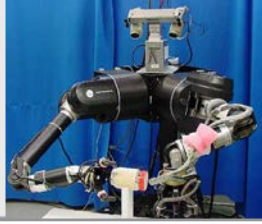

illum in tabula per radios Solis, quàm in cœlo contin-
git: hoc eſt, ſi in cœlo ſuperior pars deliquiũ patiatur, in
radiis apparebit inferior deficere, vt ratio exigit optica.

Sic nos exactè Anno .1544. Louanii eclipſim Solis
obſeruauimus, inuenimusq; deficere paulò plus q̃ dex-

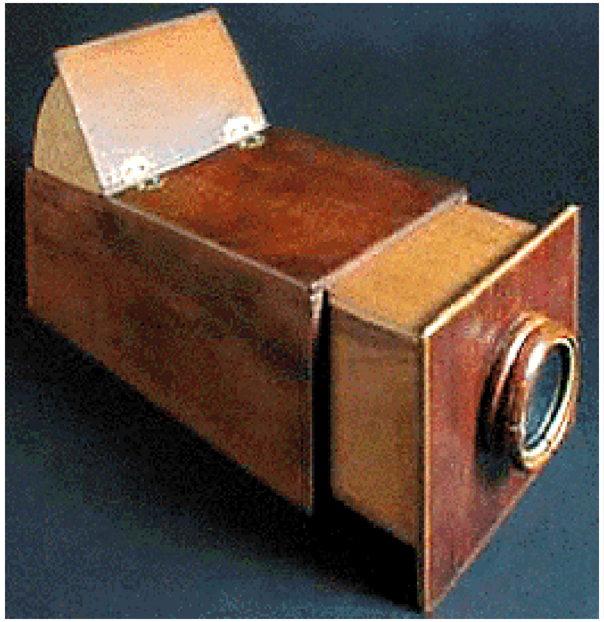
- Latin:
  - Camera for "vaulted chamber/room"
  - obscura for "dark"
  - together "darkened chamber/room“
- "When images of illuminated objects ... penetrate through a small hole into a very dark room ... you will see [on the opposite wall] these objects in their proper form and color, reduced in size ... in a reversed position, owing to the intersection of the rays". - Da Vinci

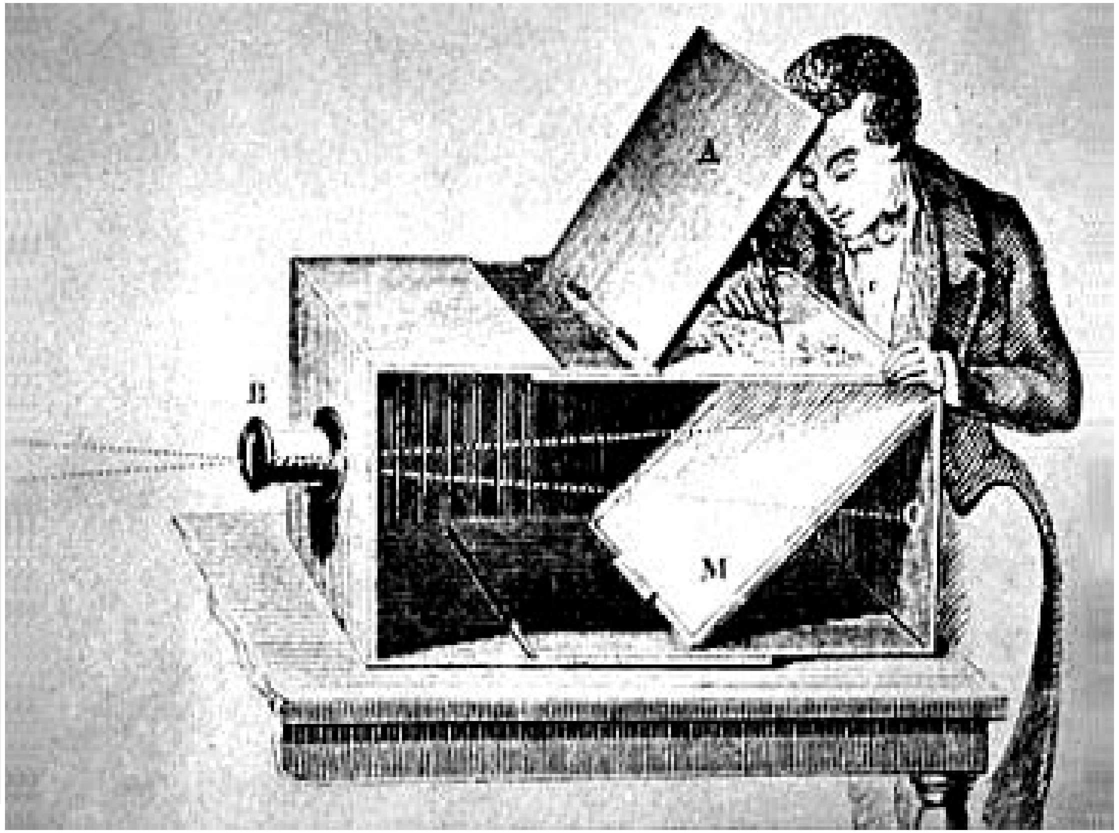
http://www.acmi.net.au/AIC/CAMERA_OBSCURA.html (Russell Naughton)

Camera Obscura

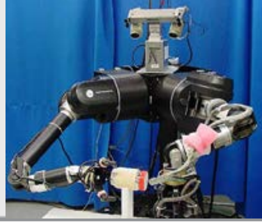


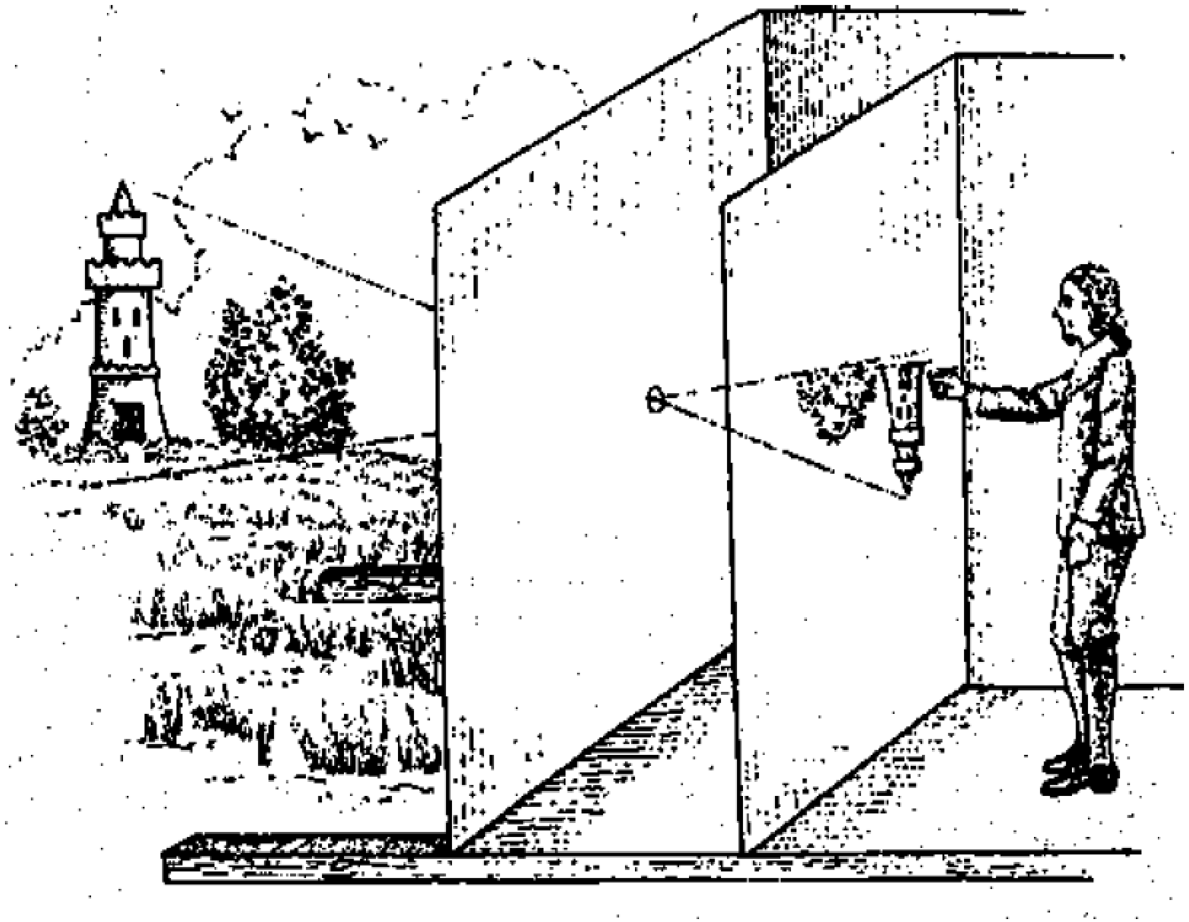
- Used to observe eclipses (eg., Bacon, 1214-1294)
- By artists (eg., Vermeer).



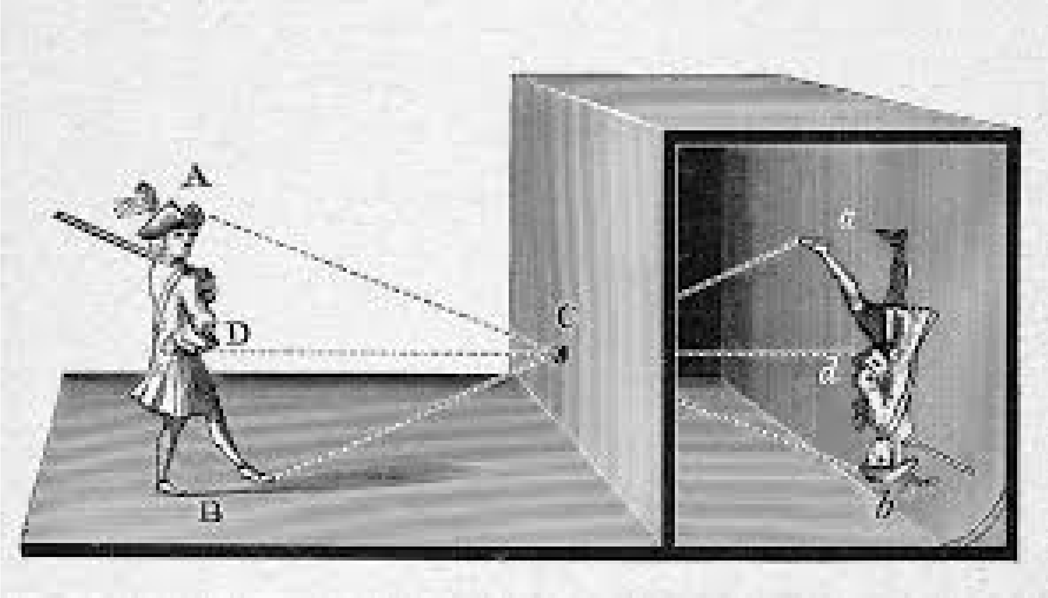


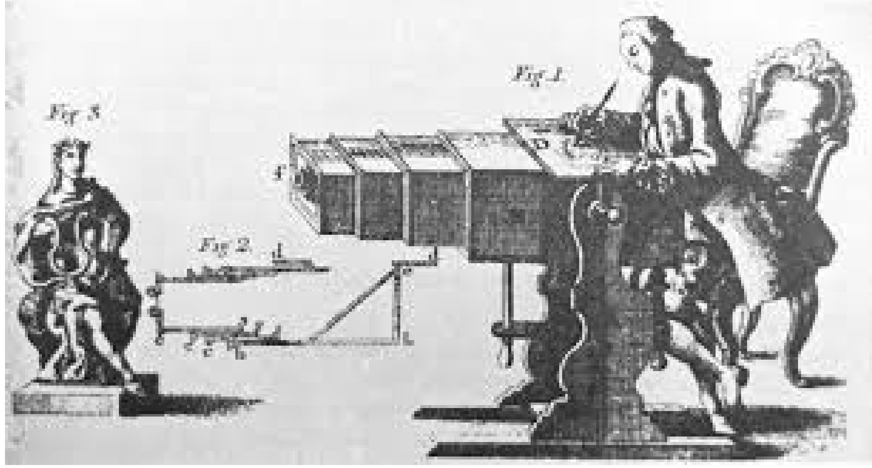
Camera Obscura

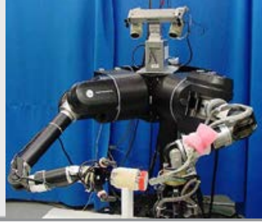




Drawing from "The Great Art of Light and Shadow "
Jesuit Athanasius Kircher, 1646.







Camera Obscura

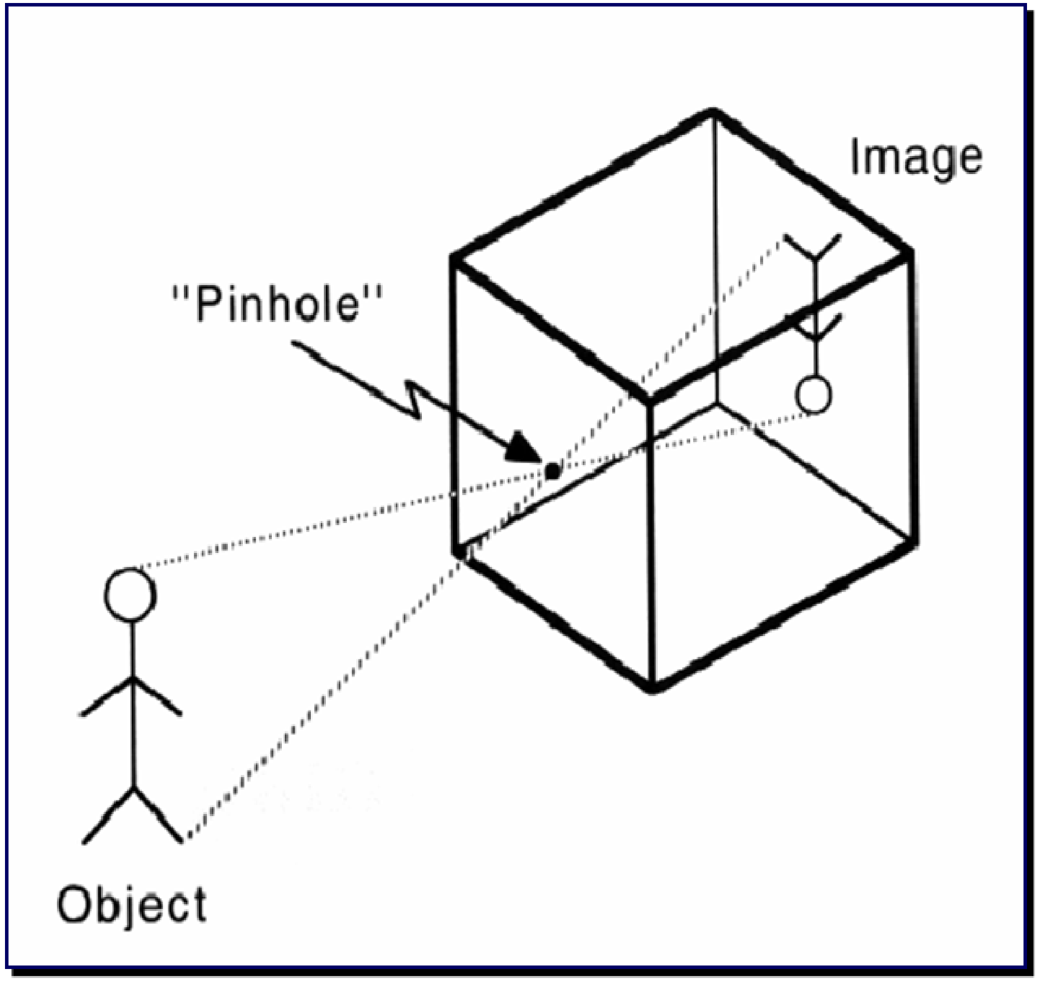
Jetty at Margate England, 1898.

Computer Vision Lab

Pinhole Camera

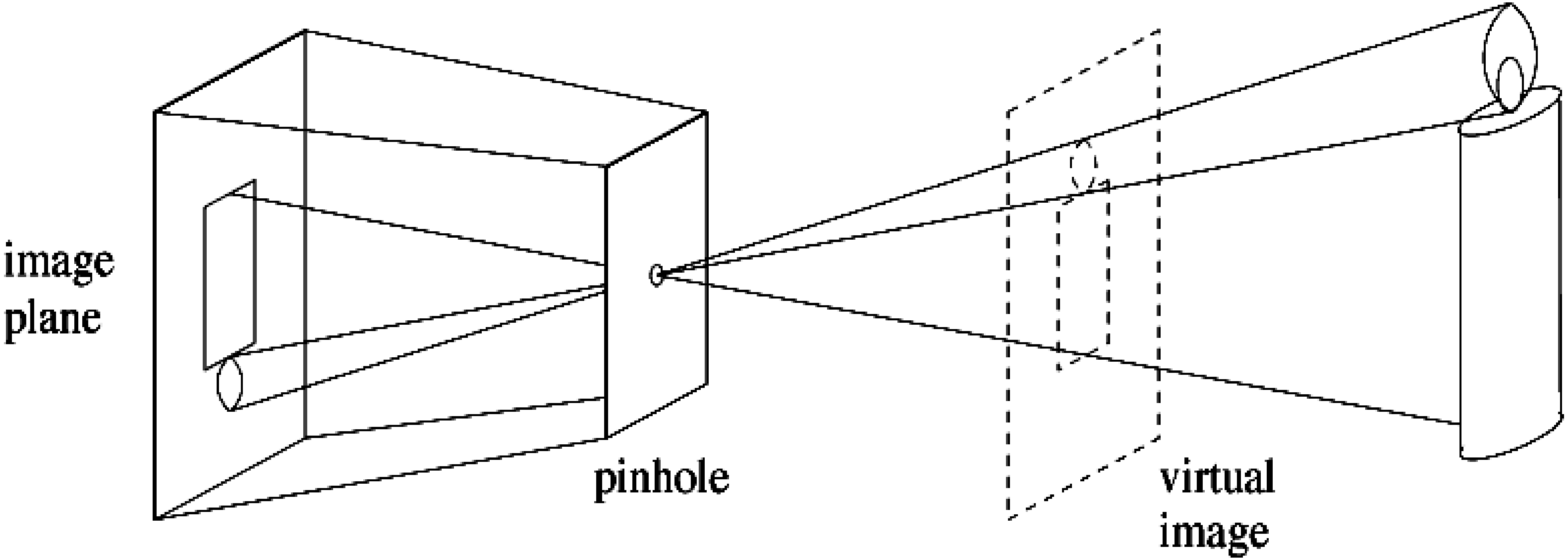
- Simple Model of Camera Obscura:

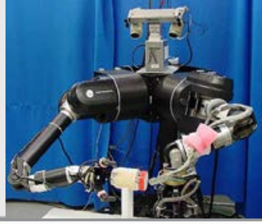
  Pinhole camera:
  - Very small hole (aperture ~ 0)
  - Light passes through the hole
  - forms image on back
  - upside down and flipped



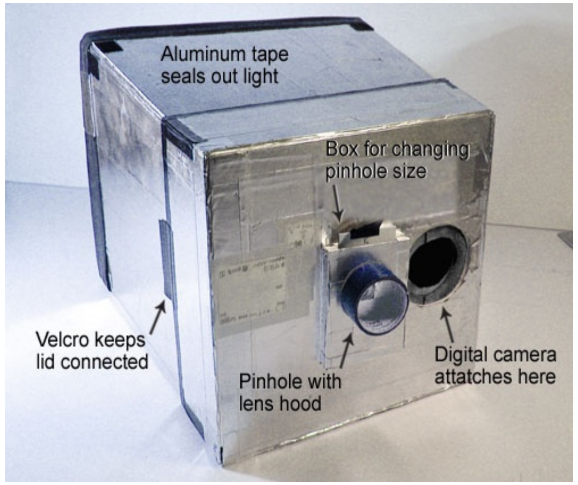
Pinhole Camera

- Abstract camera model - box with a small hole in it
- Pinhole cameras work in practice





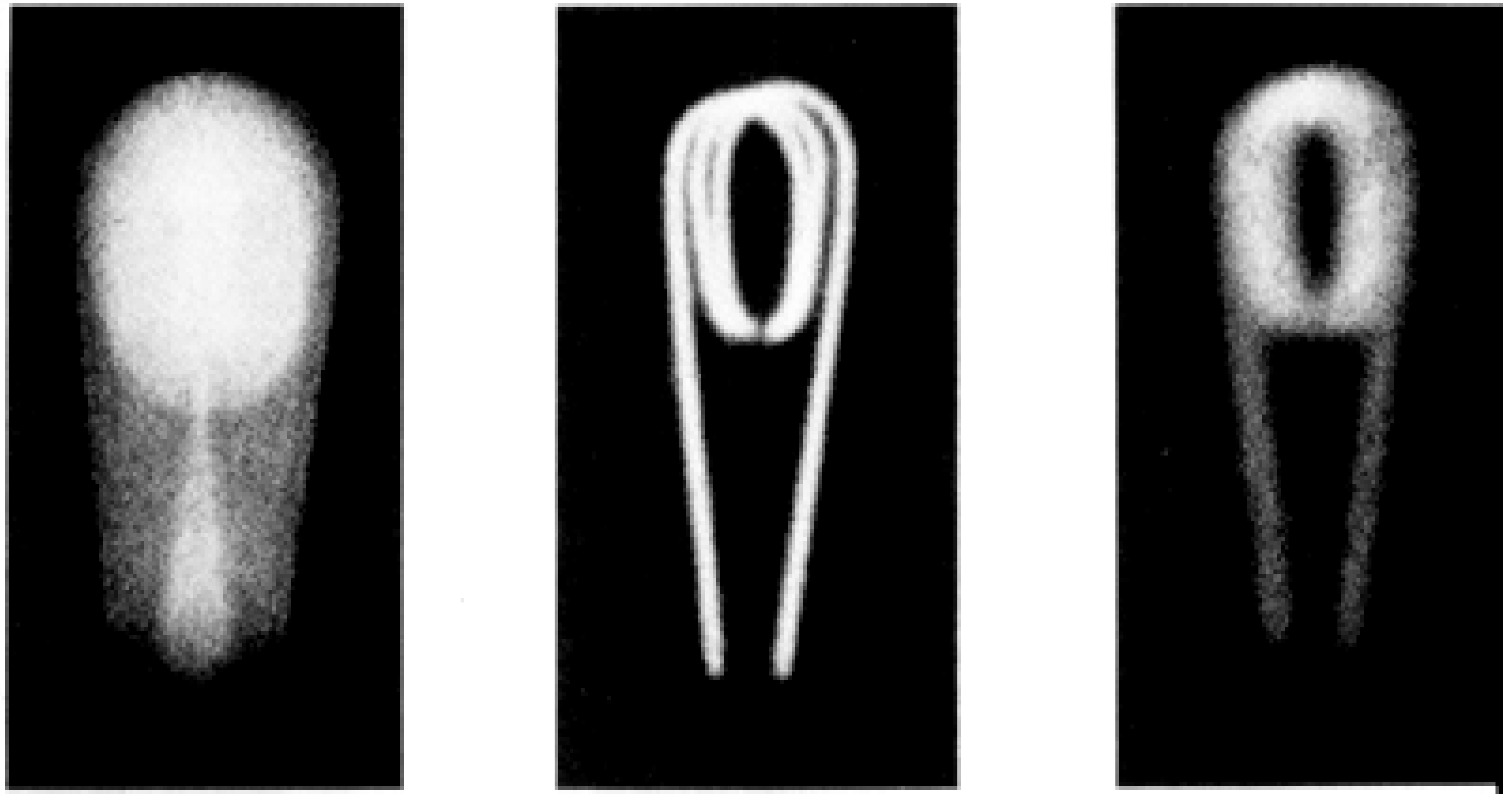
Commercial Pinhole Cameras



Limits of Pinhole Cameras

- A picture of a filament taken with a pinhole camera.

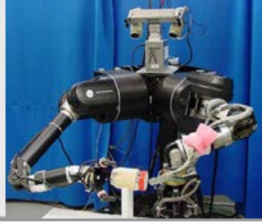
- Left: hole too big (blurring),
- Right: hole too small (diffraction)



Ruechardt, 1958

Human Eye

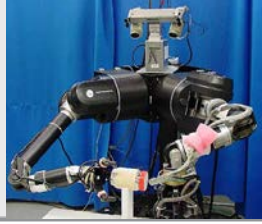
Human Eye - History



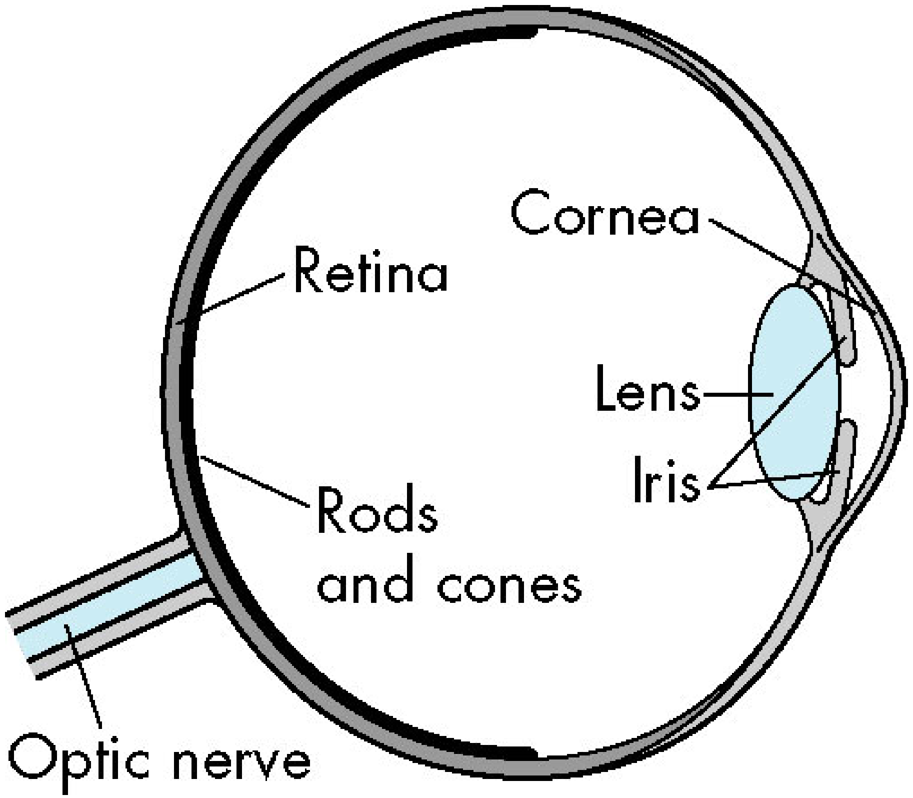
- **Pythagoras** (500 BC): Eye is **sending out rays** – by touching objects the seeing process is initiated (Range Finder Principle)

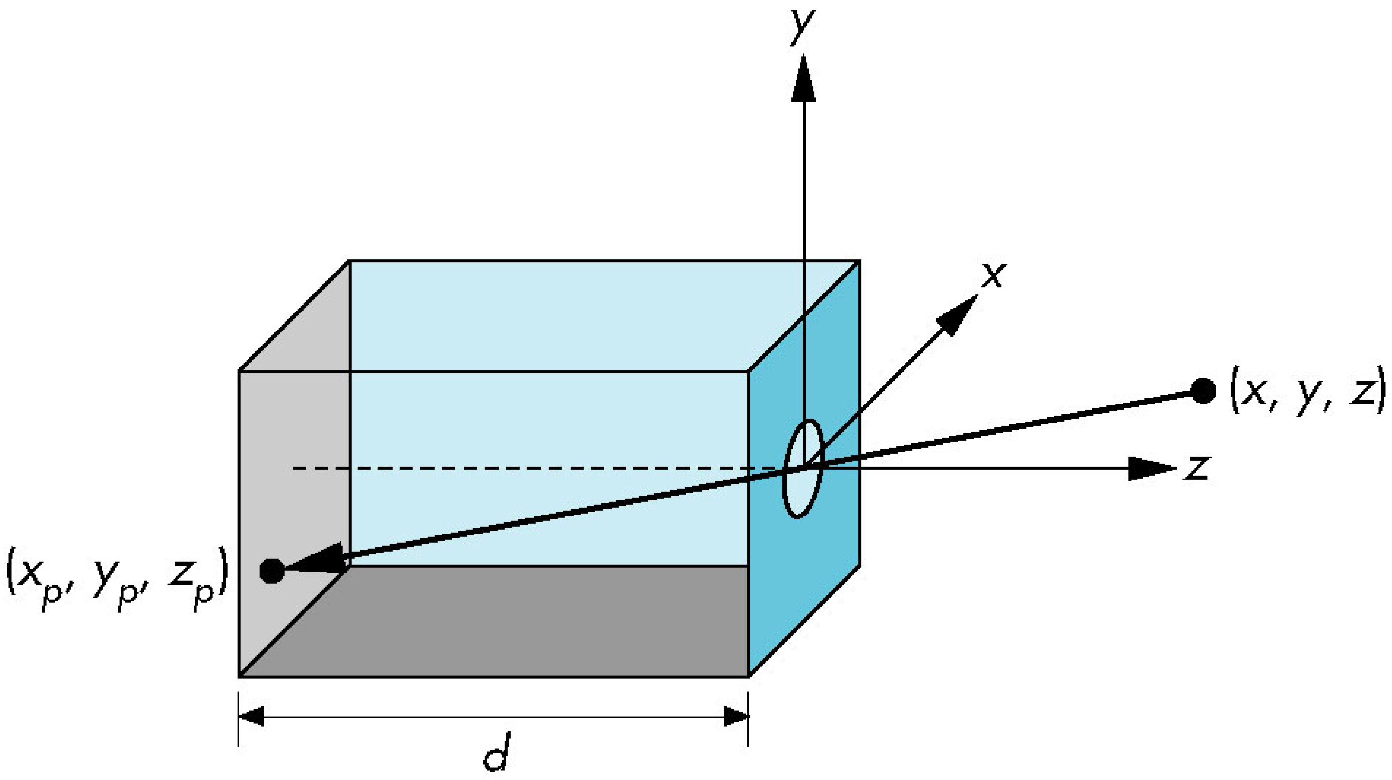
- **Keppler** (1604 AD): discovers vision process in human eye. On the retina an **upside-down image** of the world is sensed, which is assembled in the **visual center** into a 3d image.

Human Eye vs. Camera



- We make cameras that act “similar” to the human eye





Human Eye

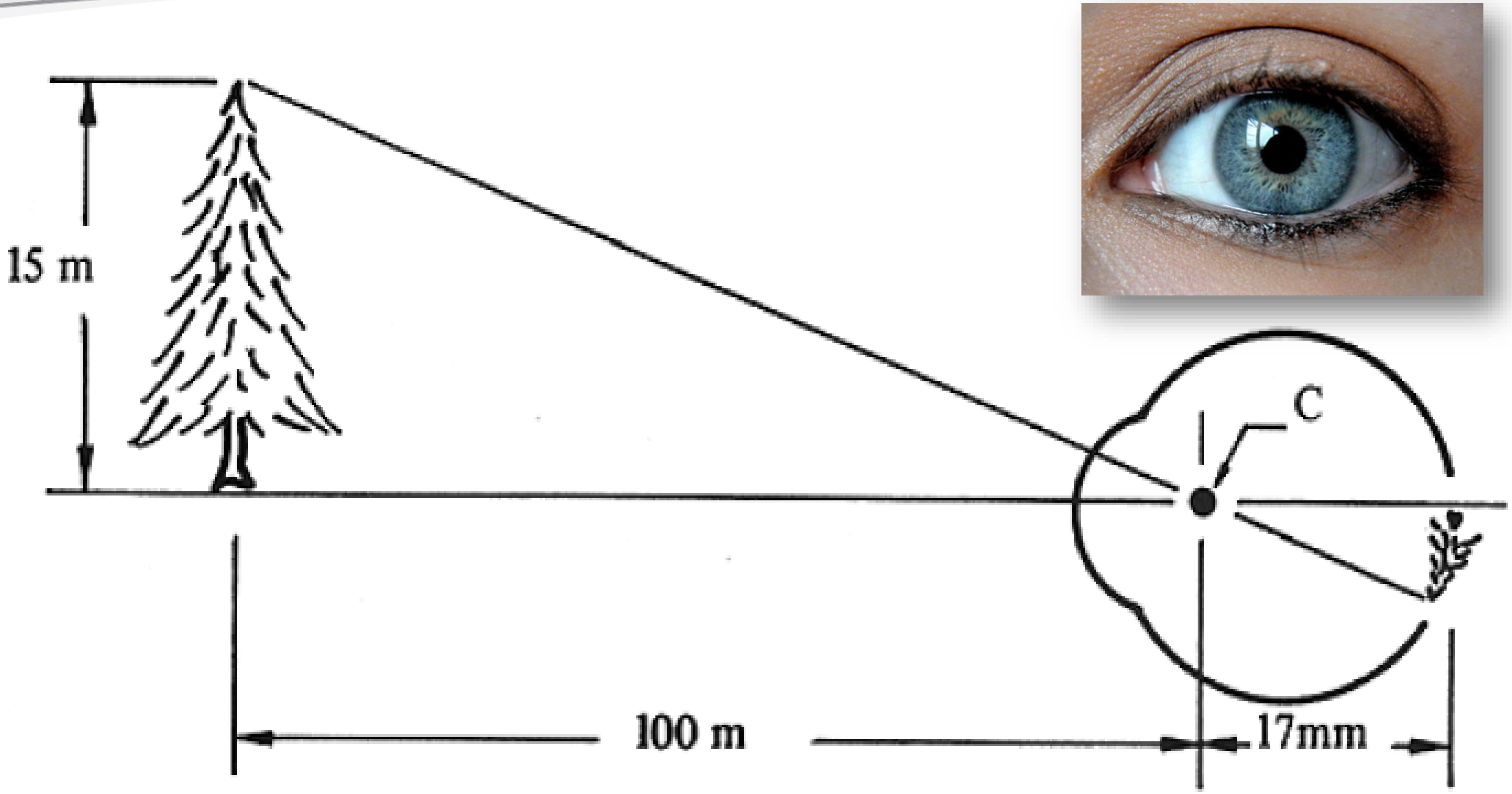
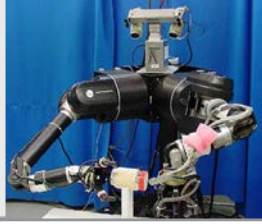
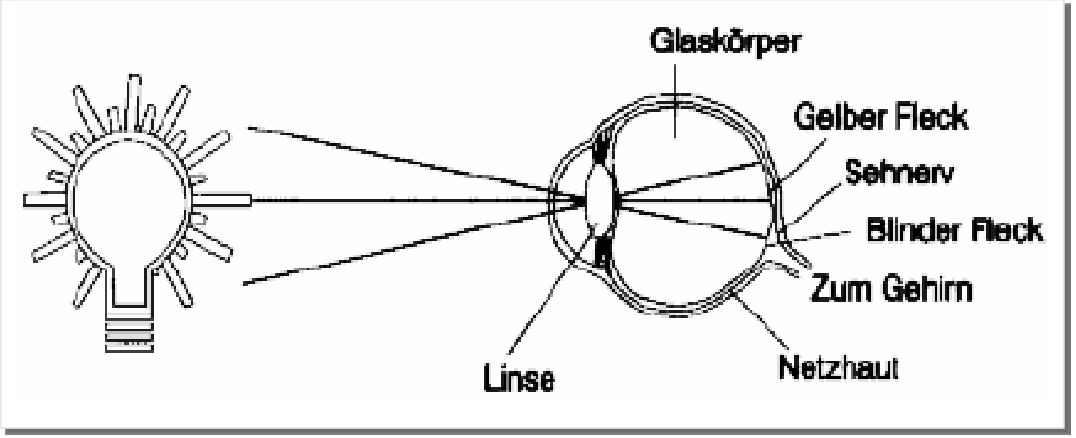


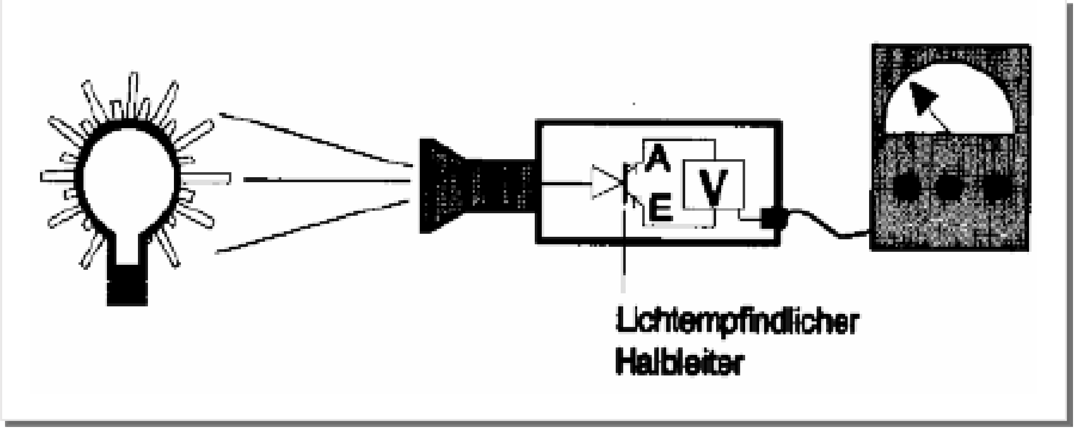
Image Formation



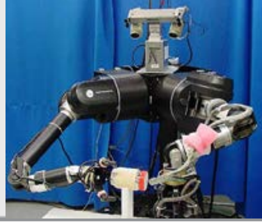
- **Input in Human Vision:**
  - Eye



- **Input in Computer Vision:**
  - Image
  - Role model: Human eye
  - Replica: CCD camera
  - Furthermore: Scanner, 3d Scanner, ….

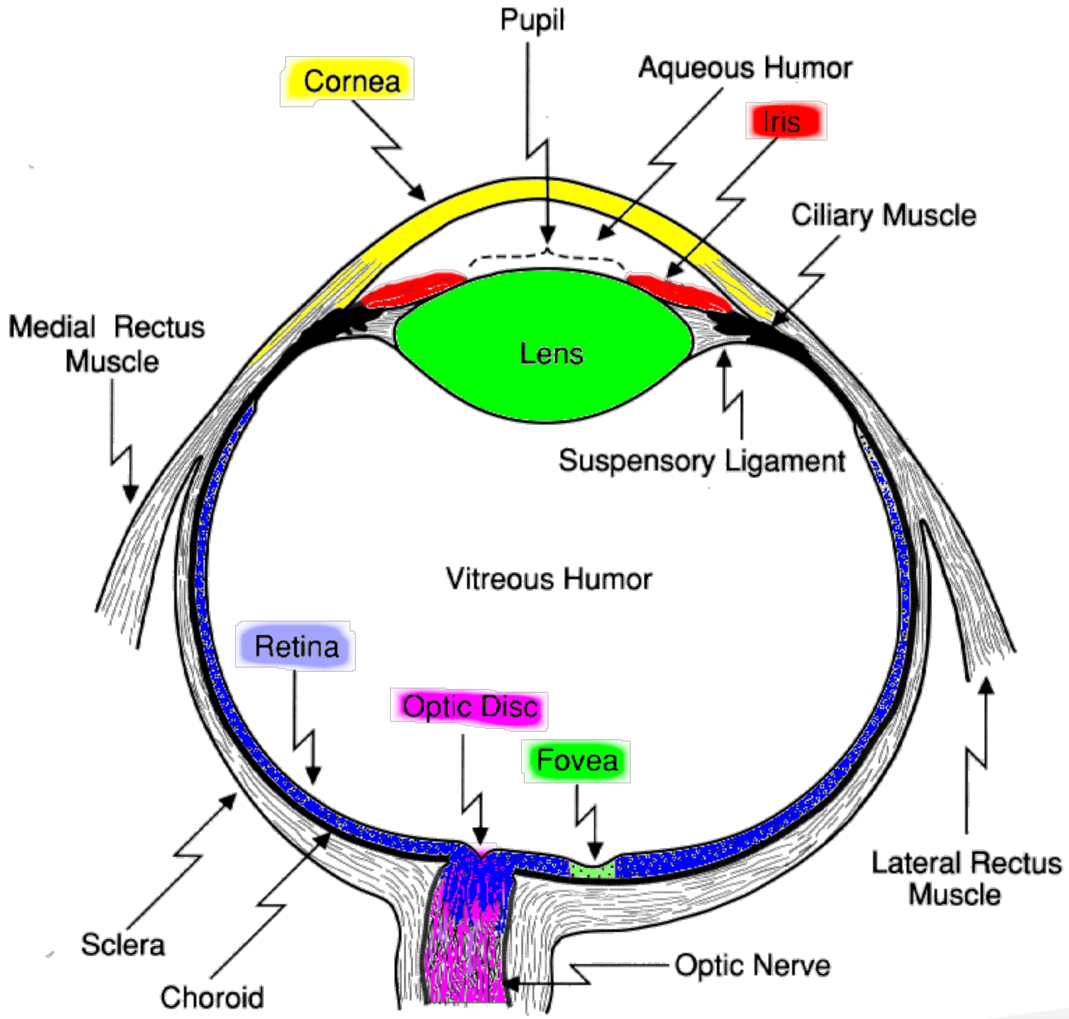


Human Eye - Accomodation



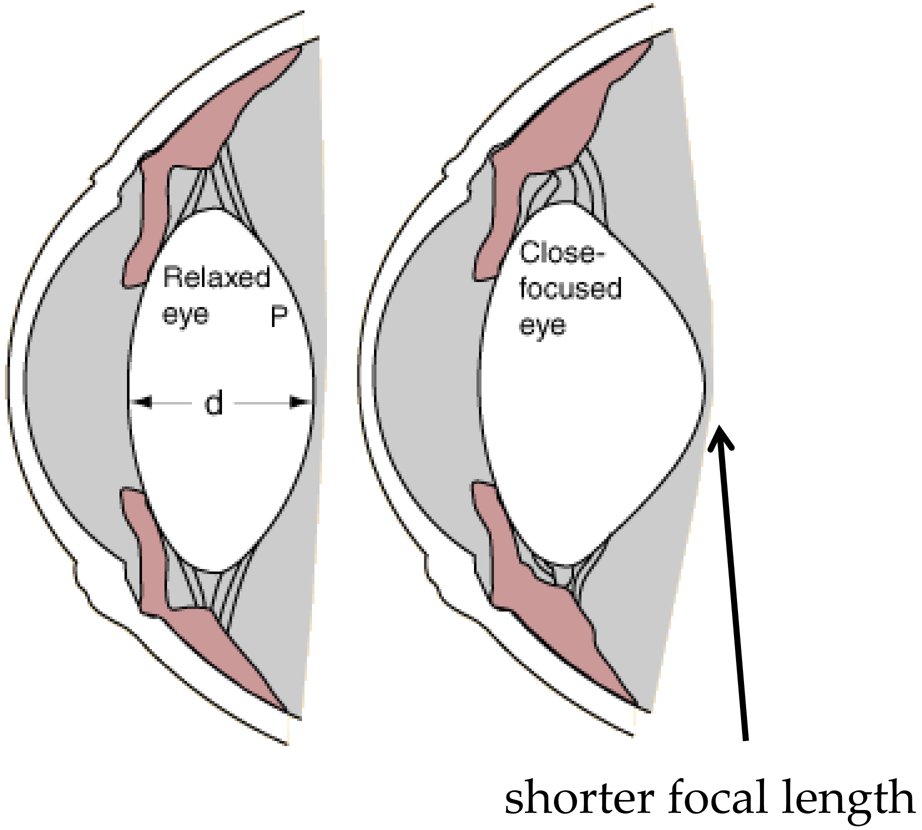
- Is the process by which the vertebrate **eye changes optical power** to maintain a **clear image (focus)** on an object **as its distance varies.**

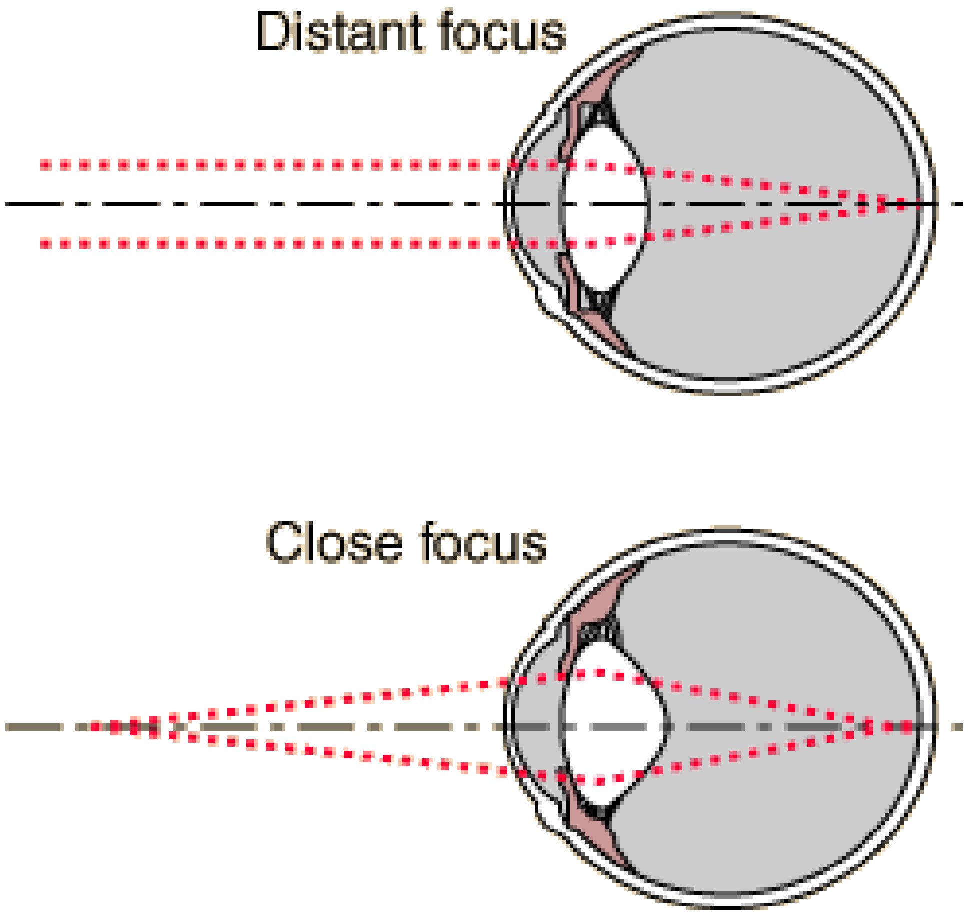
- The image of the world is **represented exactly** on the retina. Objects too far forward or too far back to be mapped are **blurred**.



Accommodation

- Changes the focal length of the lens:

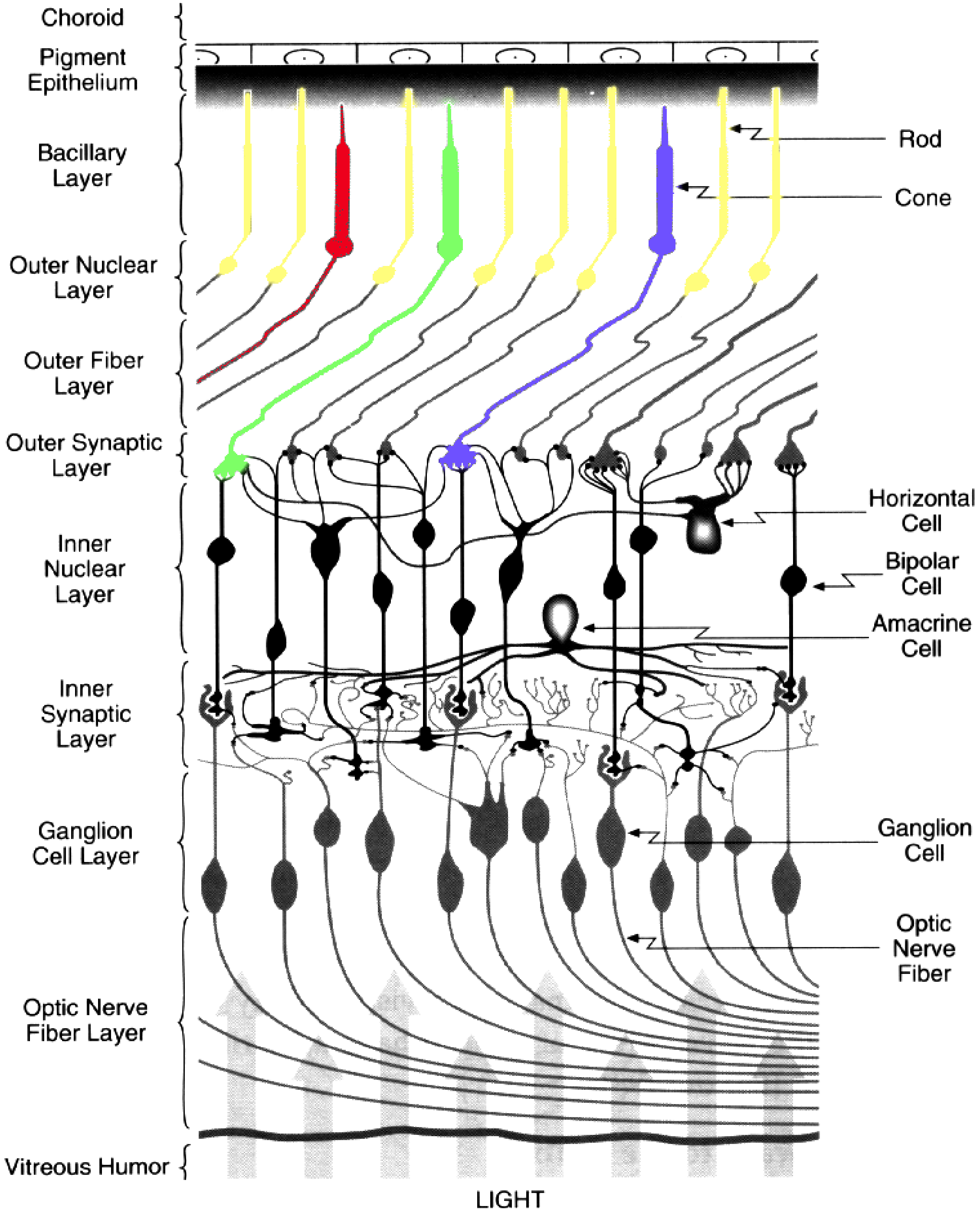




Retina

- Rods: Monochrome
- Cones: Color (RGB)
- Fovea: Cones only
- Number: 6 Mio. Cones
  120 Mio. Rods

- But only **1 Mio. nerve fibers** in optic nerve => **intelligent sensor**!

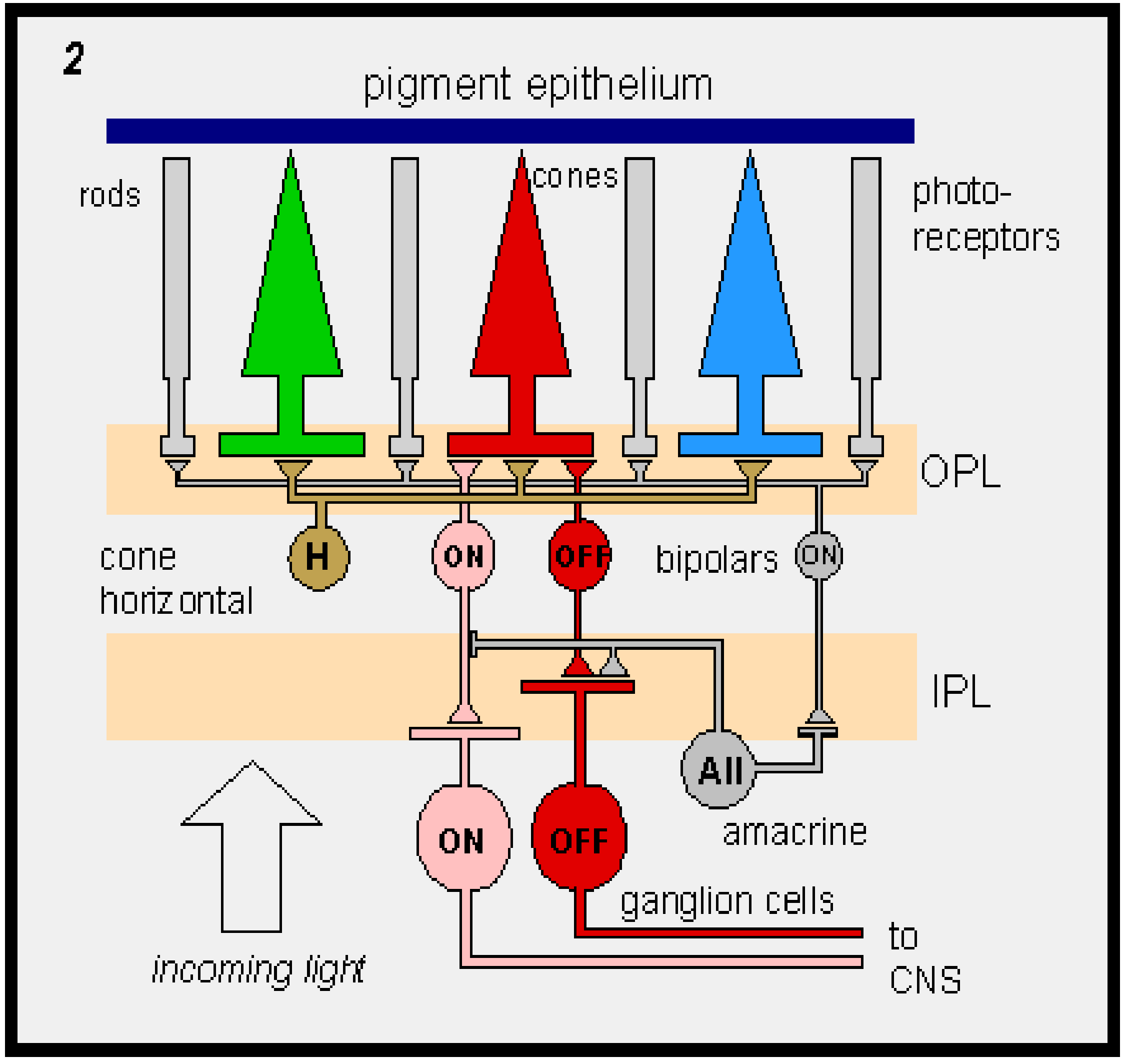


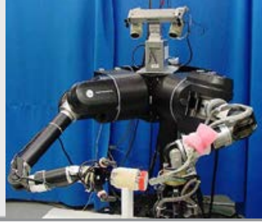
Blind Spot in Eye

Close your right eye and look directly at the “+”

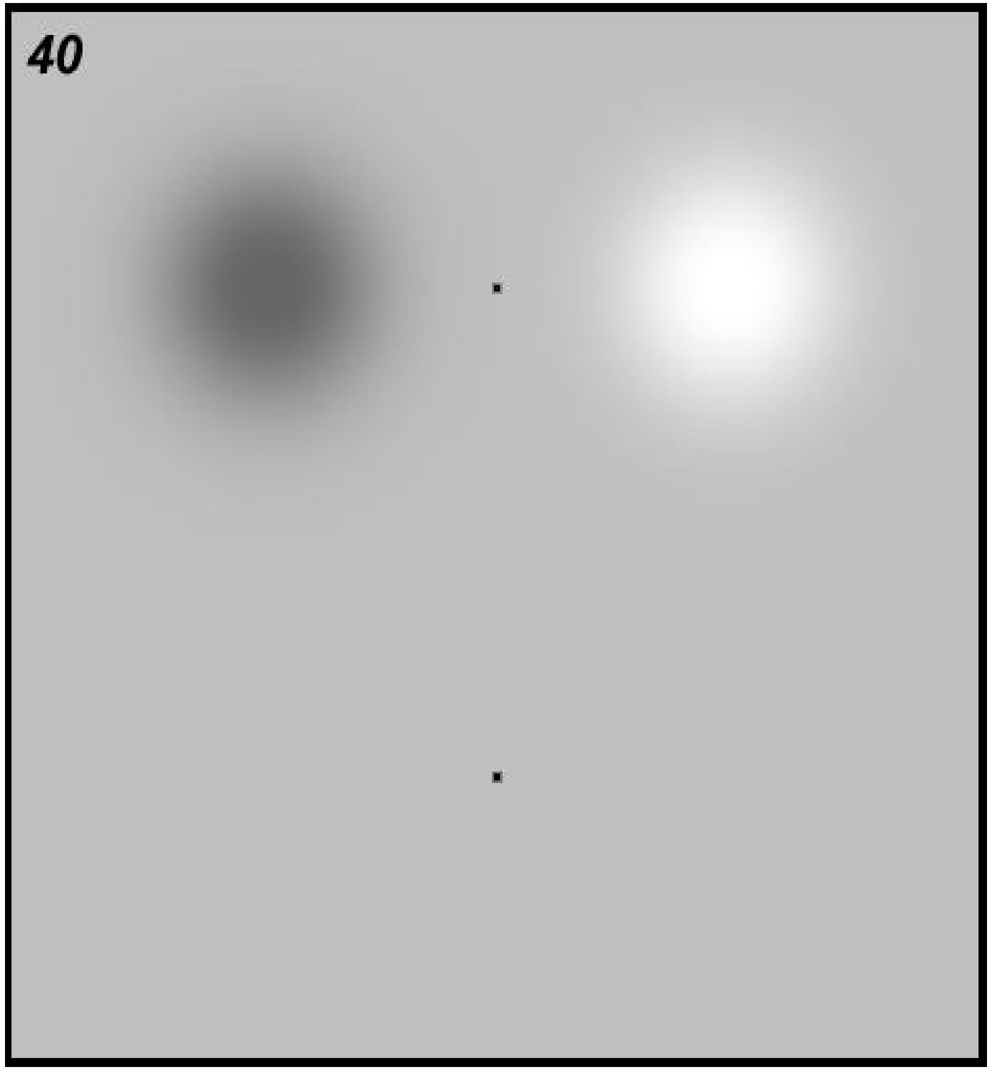
Cells of Retina

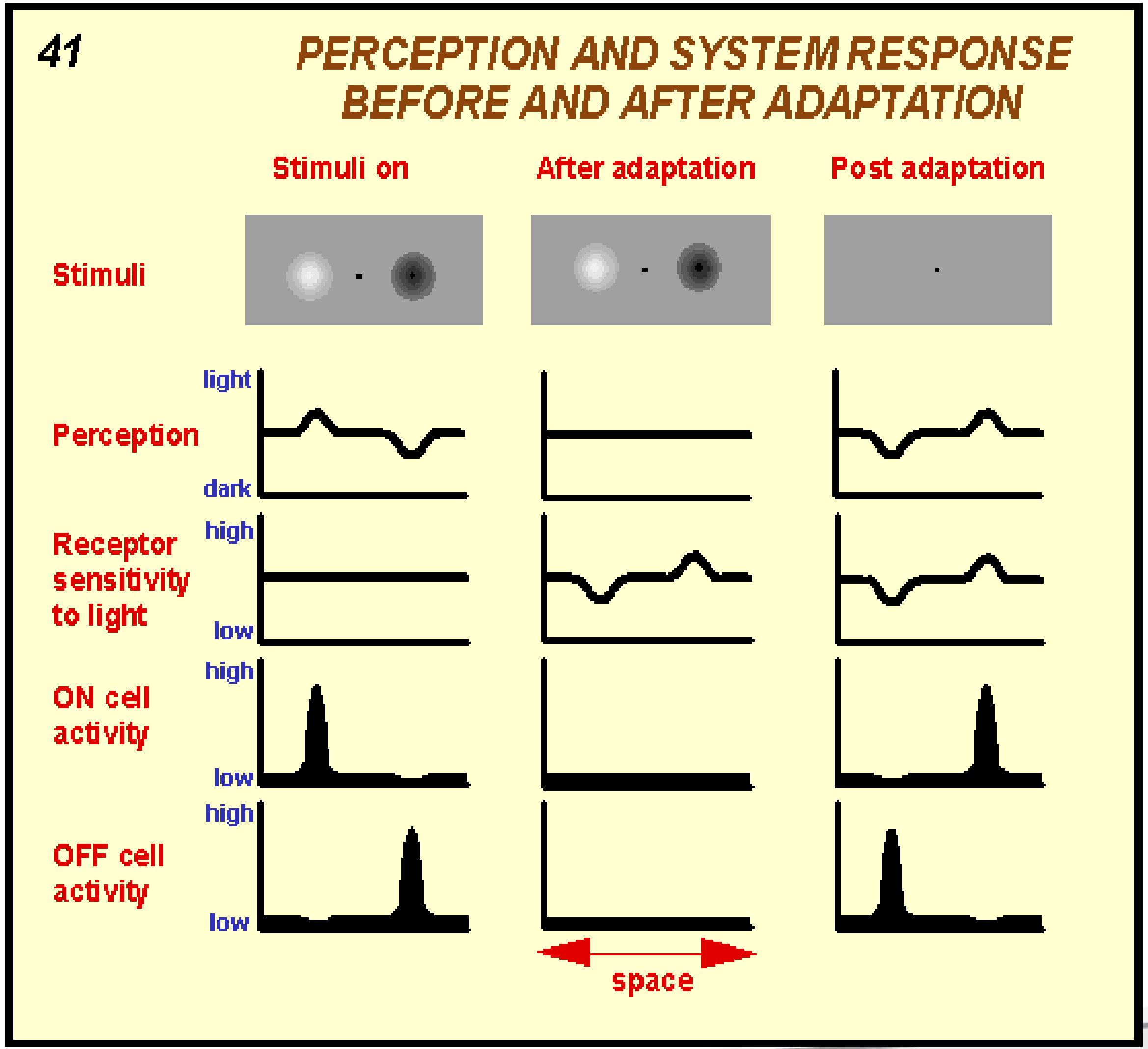
- Rods
- Cones
- Filter cells
  - Horizontal
  - Bipolar
  - Amacrine



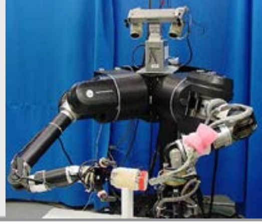


Afterimages

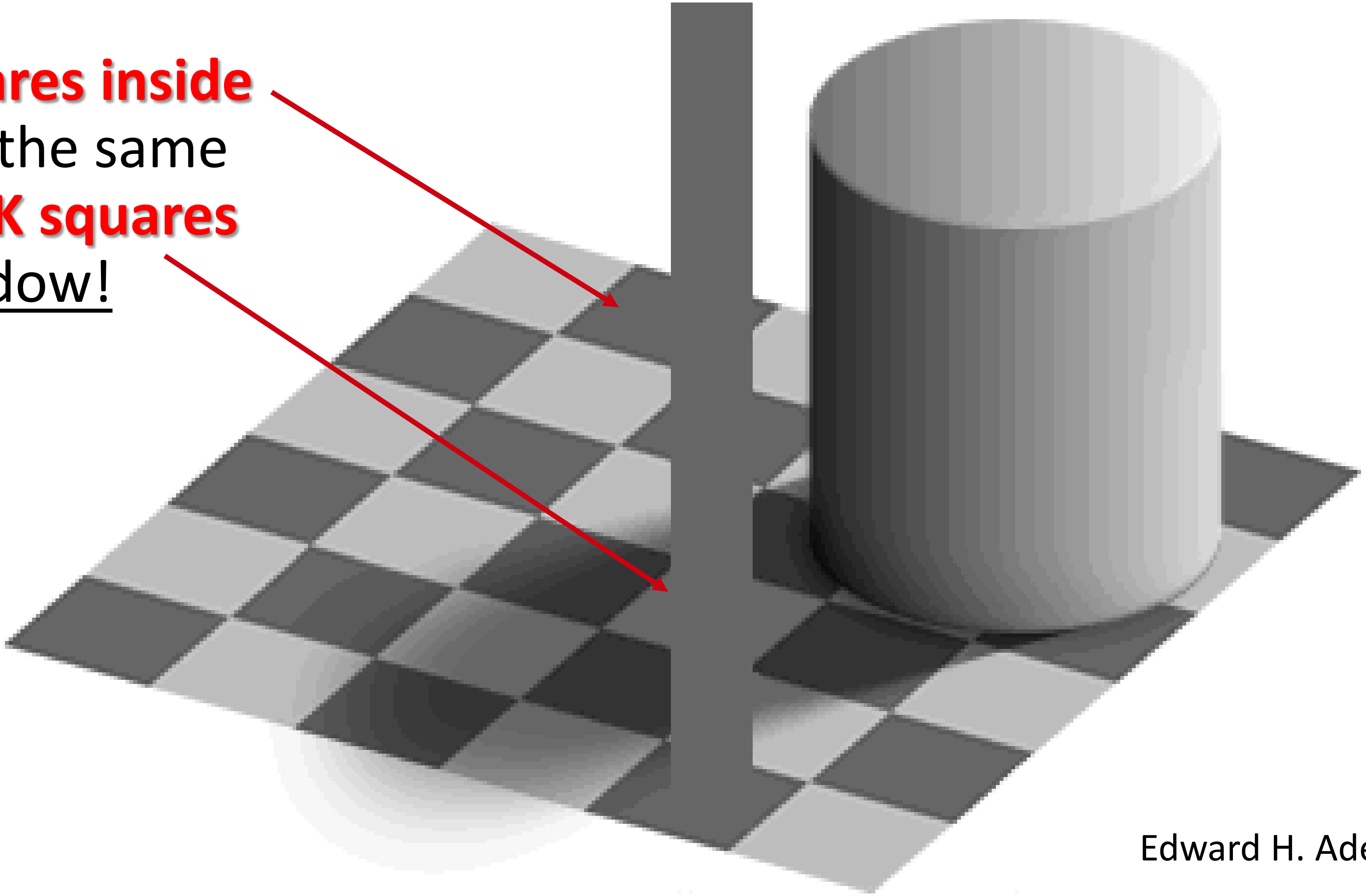




Color Constancy

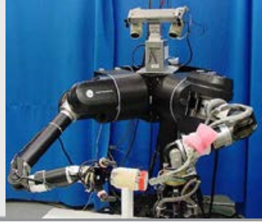


- The **WHITE squares inside** the shadow are the same grey as the **DARK squares outside** the shadow!

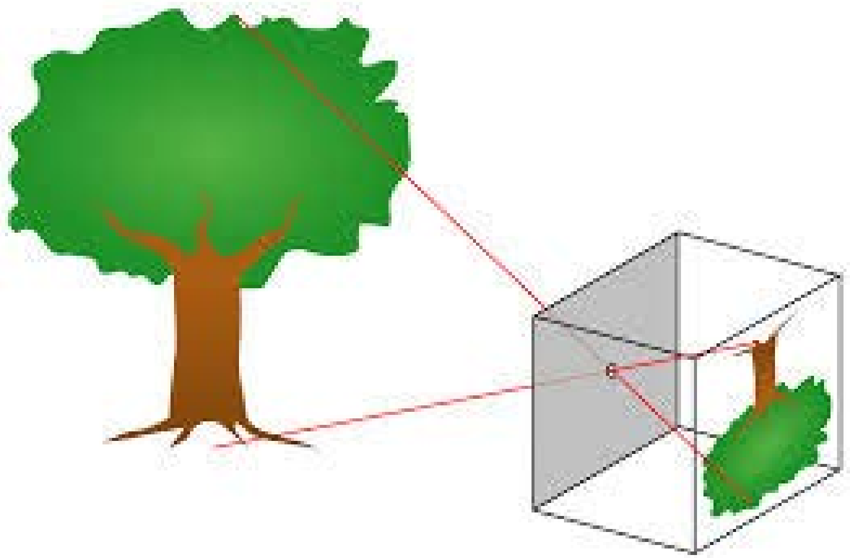


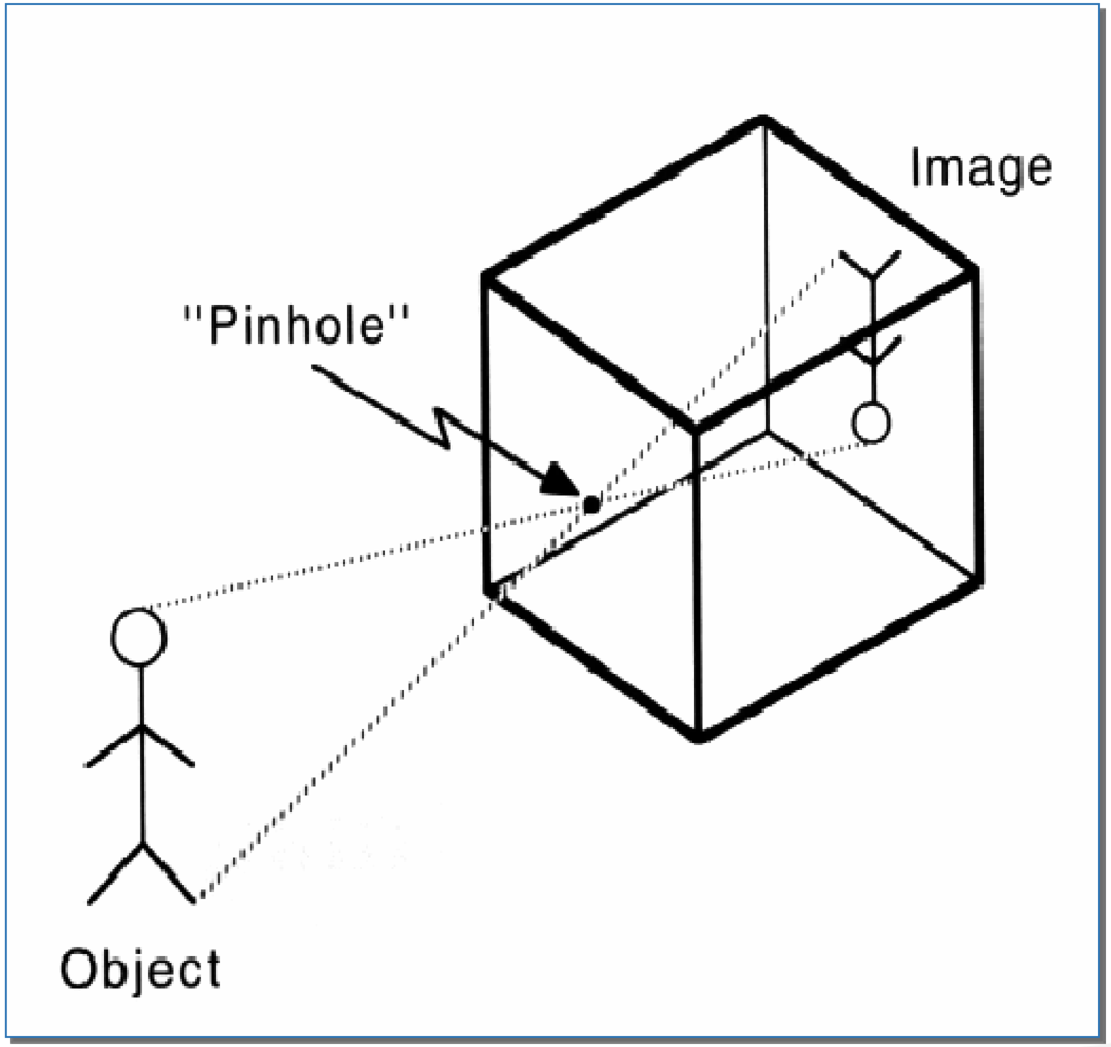
Edward H. Adelson

Image Geometry



- Simplest Model: Pinhole Camera
  - Has a very small hole (Aperture = ∞), Light is led through the hole and forms an image at the back of the box (upside down and side-inverted)

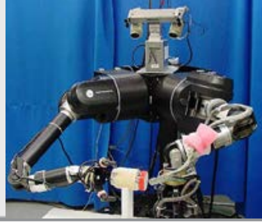




Earliest Surviving Photograph

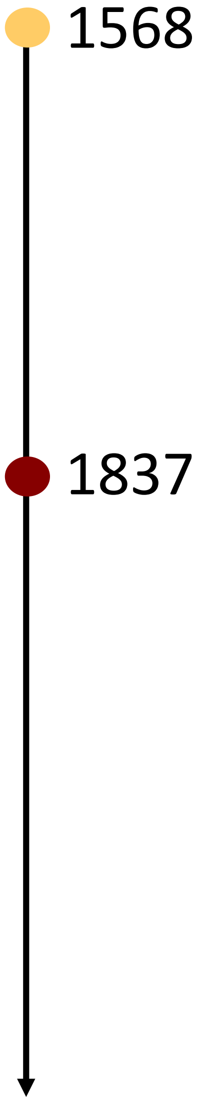
- First photograph on record, “La table service” by Nicephore Niepce in 1822.

A Brief History of Images

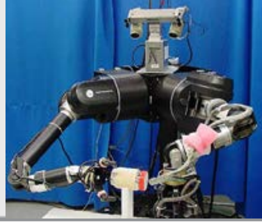


Louis Jaques Mande Daguerre, 1844

Still Life, Louis Jaques Mande Daguerre, 1837



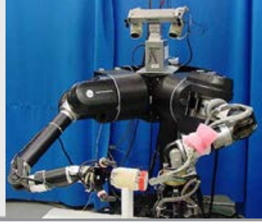
A Brief History of Images



1568

1840?

Abraham Lincoln 1840?



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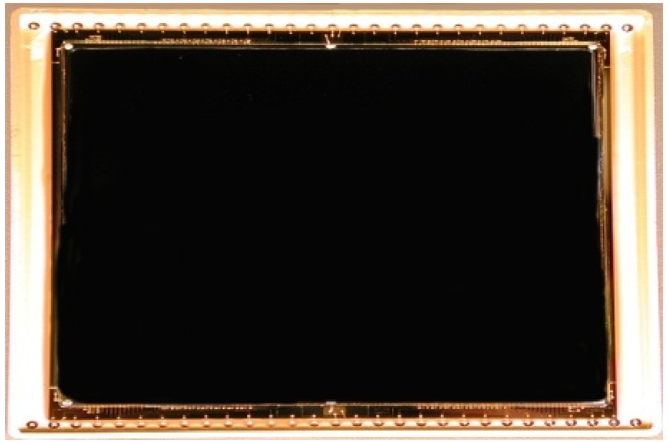
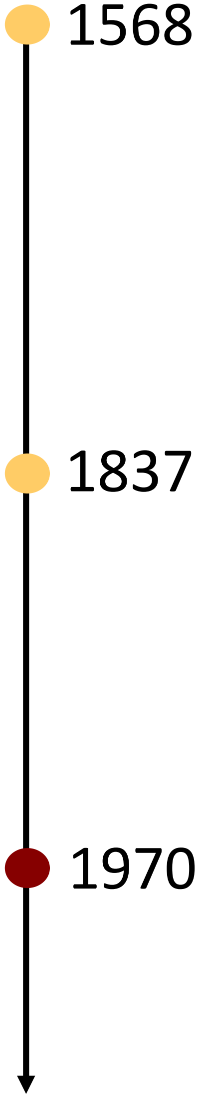
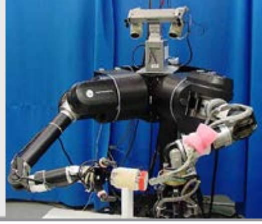


Silicon Image Detector, 1970



A Brief History of Images



- Digital Cameras

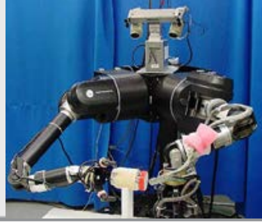
1568

1837

1970

1995

A Brief History of Images



- Nikon D810A, 36,1 MPix

1568

1837

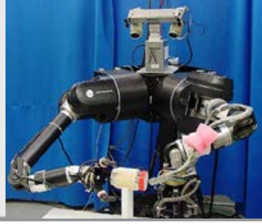
1970

1995

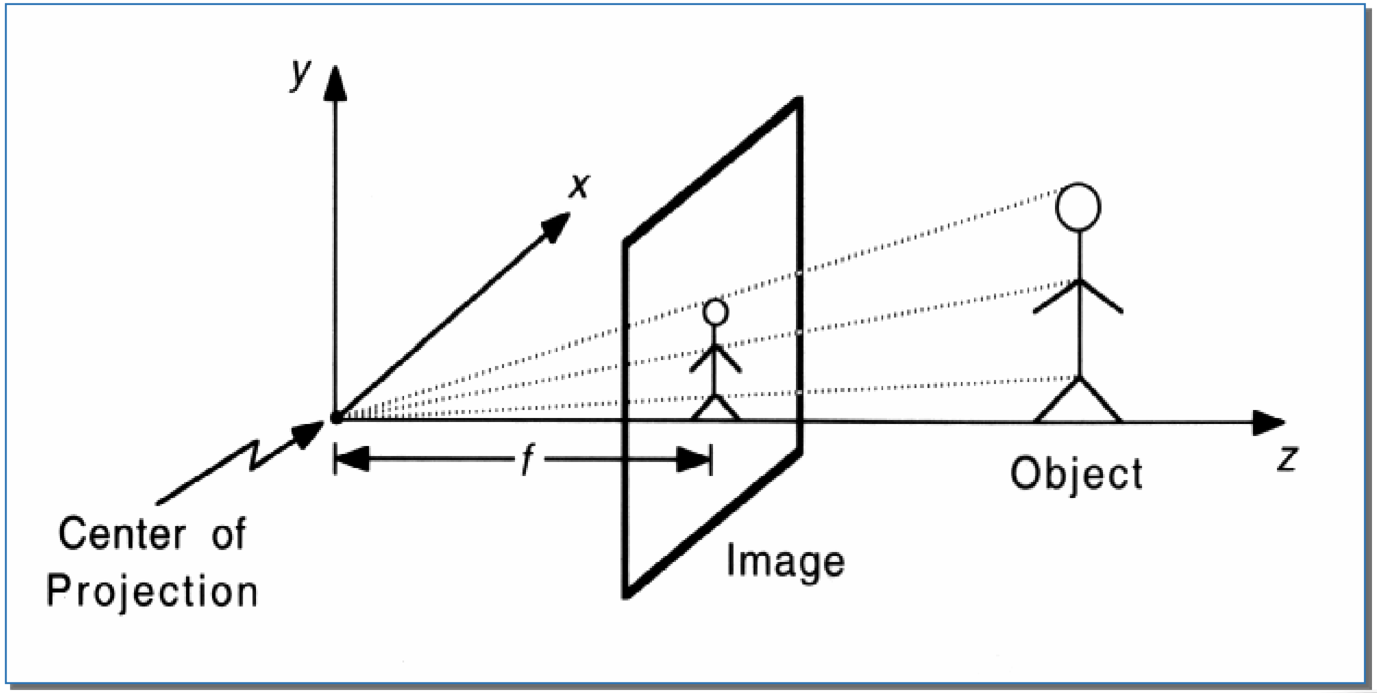
2015

Image Formation

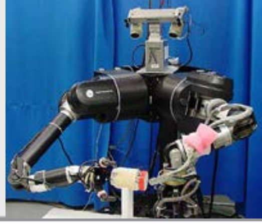
Image Geometry



- Perspective Projection (Central projection)
  - Is the projection of the 3d world onto a 2d plane by rays passing through a common point the center of projection.
  - => models image formation by a pinhole camera

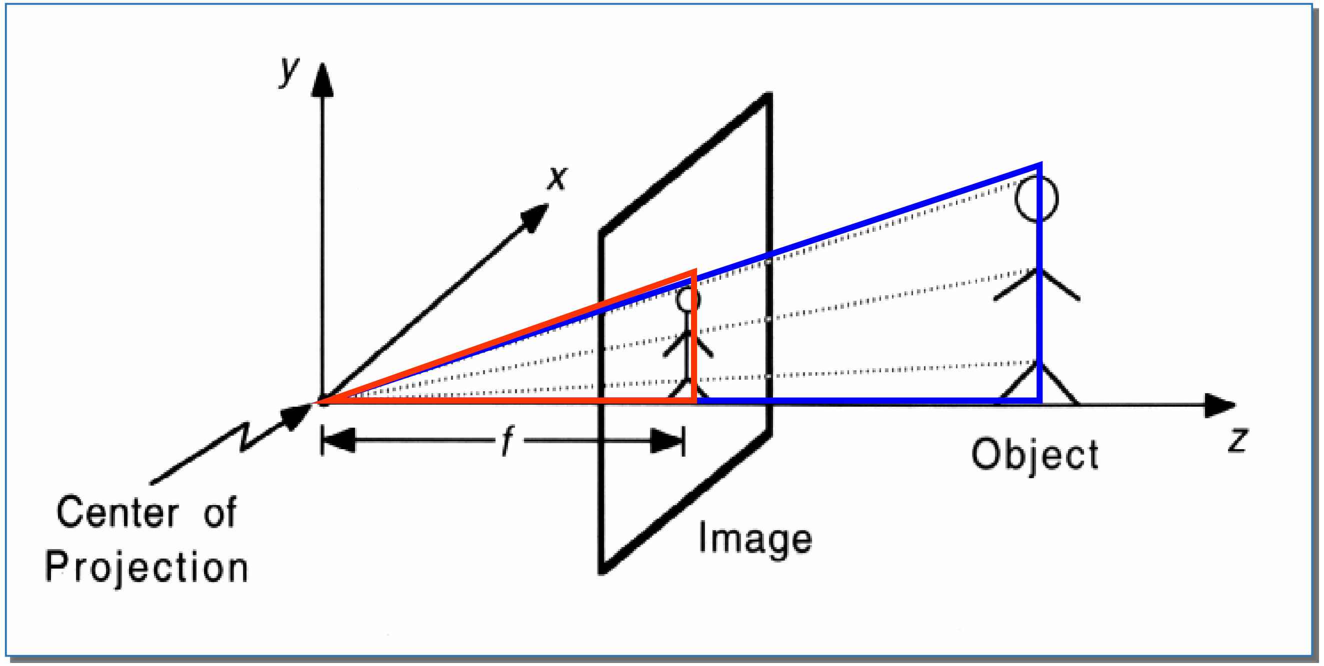


Equations of the Perspective Projection



$$x = \frac{f}{Z} X$$

$$y = \frac{f}{Z} Y$$

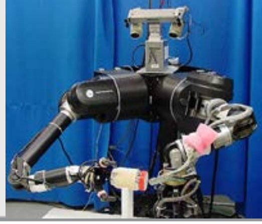


$$\frac{x}{X} = \frac{f}{Z}$$

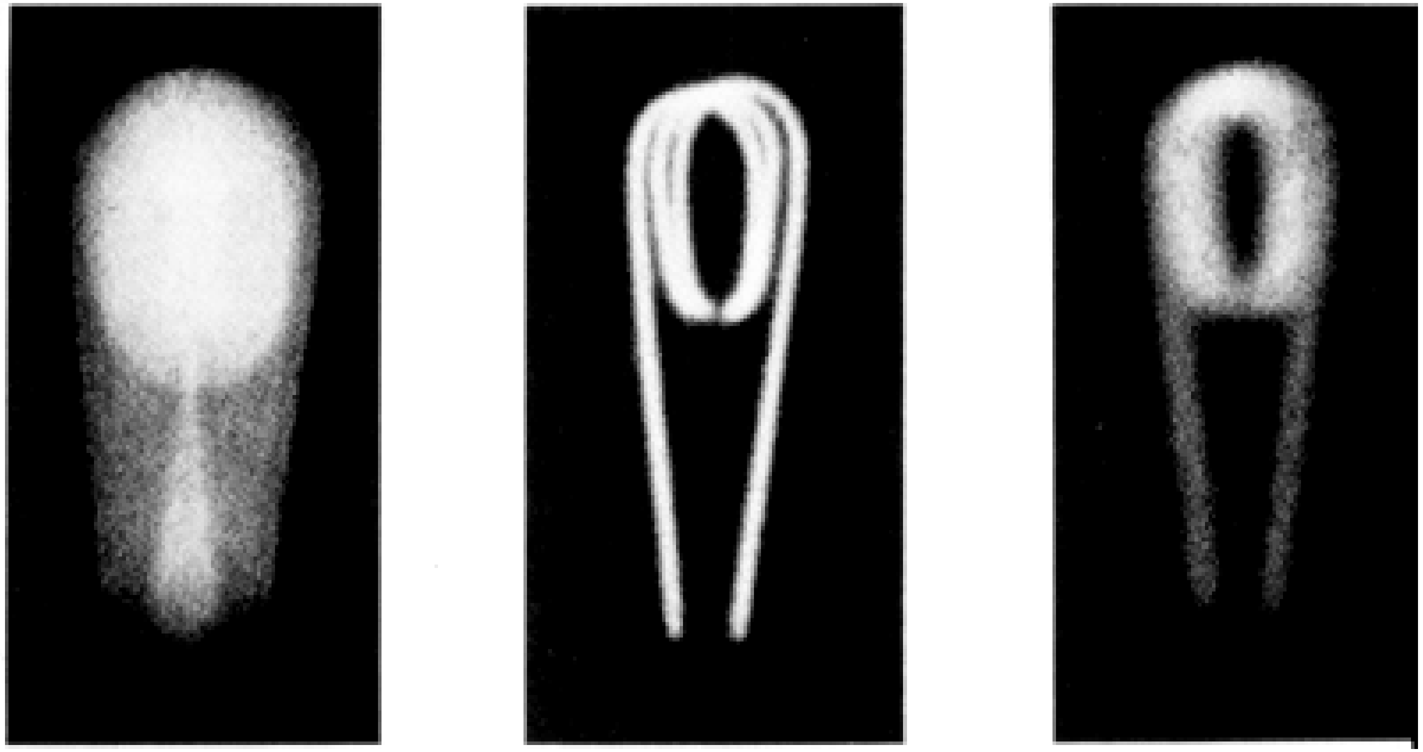
$$\frac{y}{Y} = \frac{f}{Z}$$

- Perspective projection is non-linear !

Recap: Limits of Pinhole Cameras

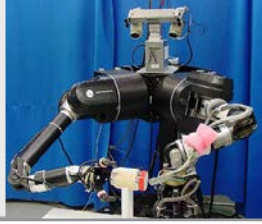


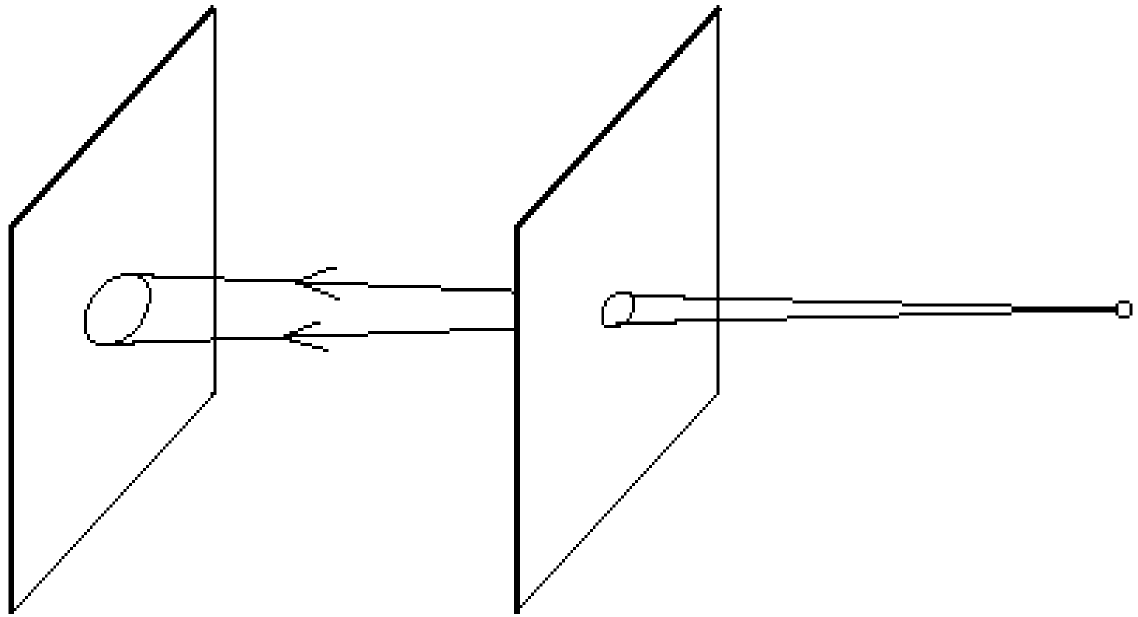
- A picture of a filament taken with a pinhole camera. In the image on the left, the hole was too big (blurring), and in the image on the right, the hole was too small (diffraction).

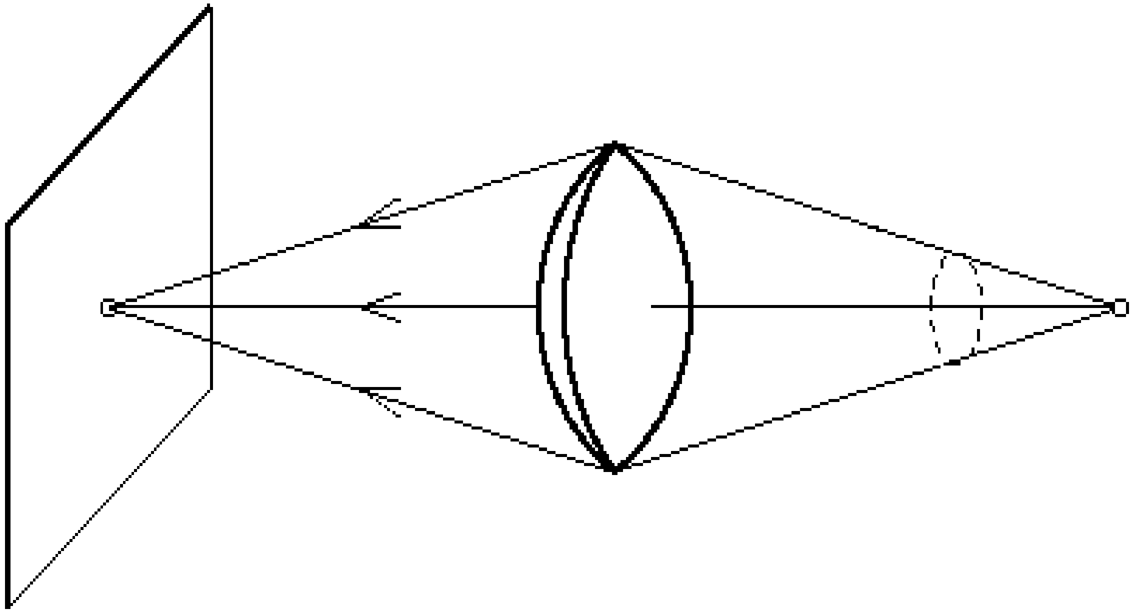


Ruechardt, 1958

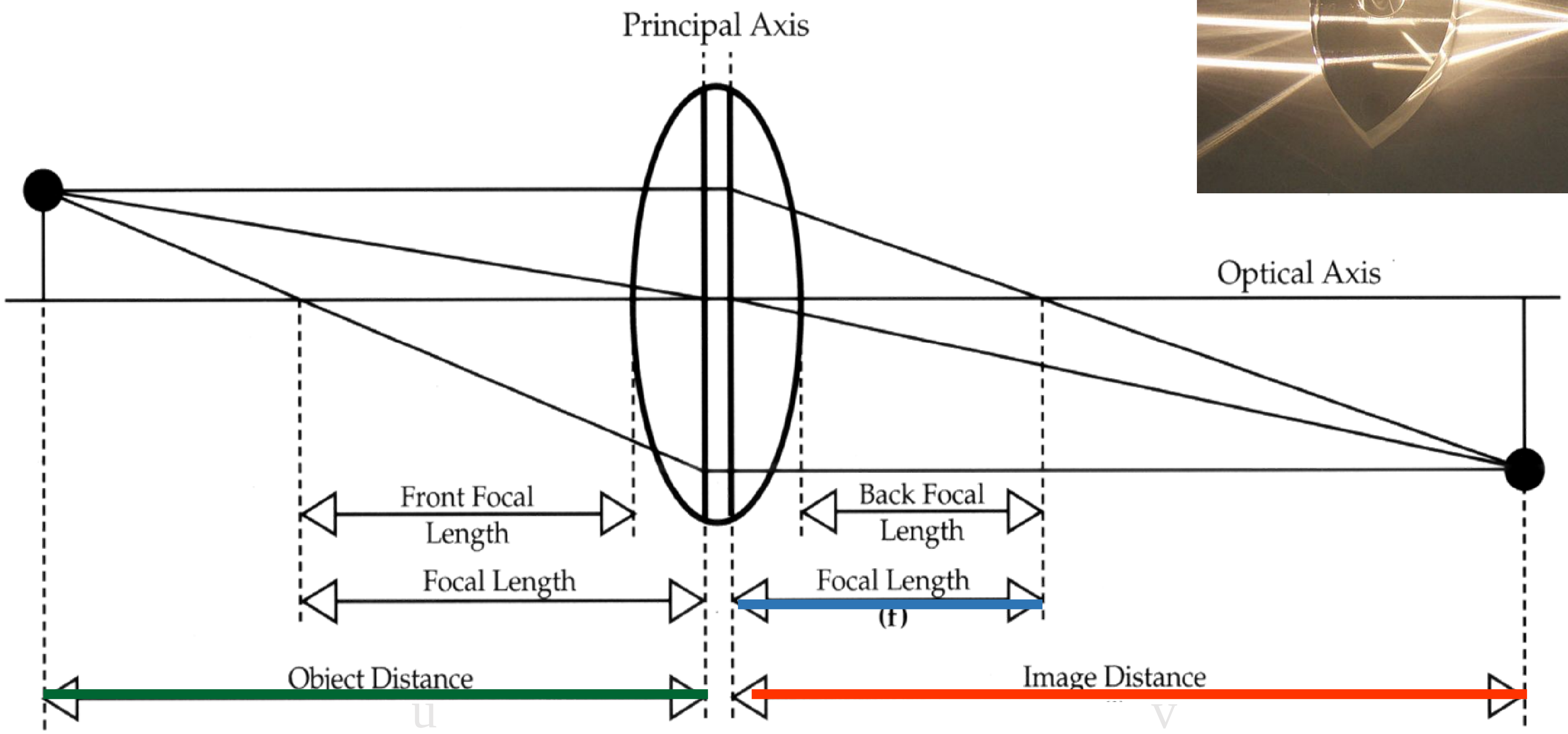
Cameras with Lenses

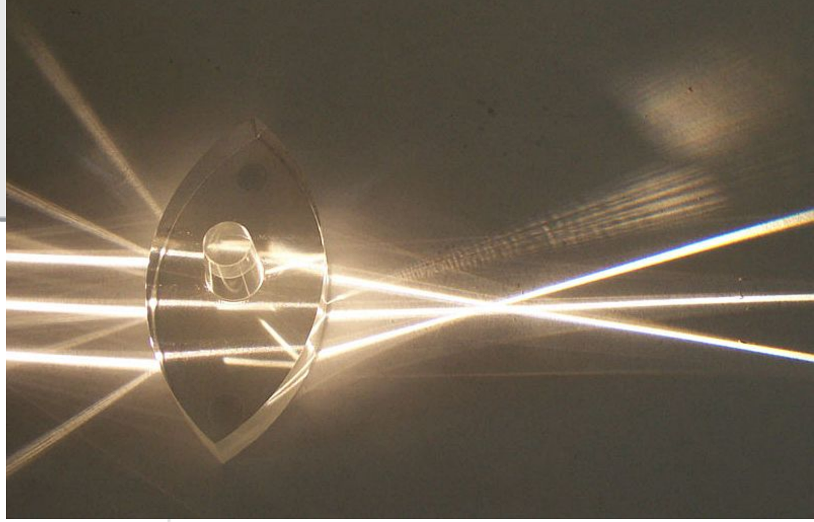






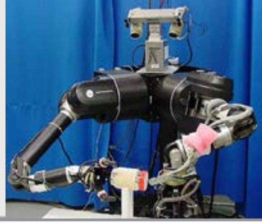
Simple Lens Parameters





FOCAL LENGTH = Distance from focus point to principal axis.

Lenses



- Pin has no lens

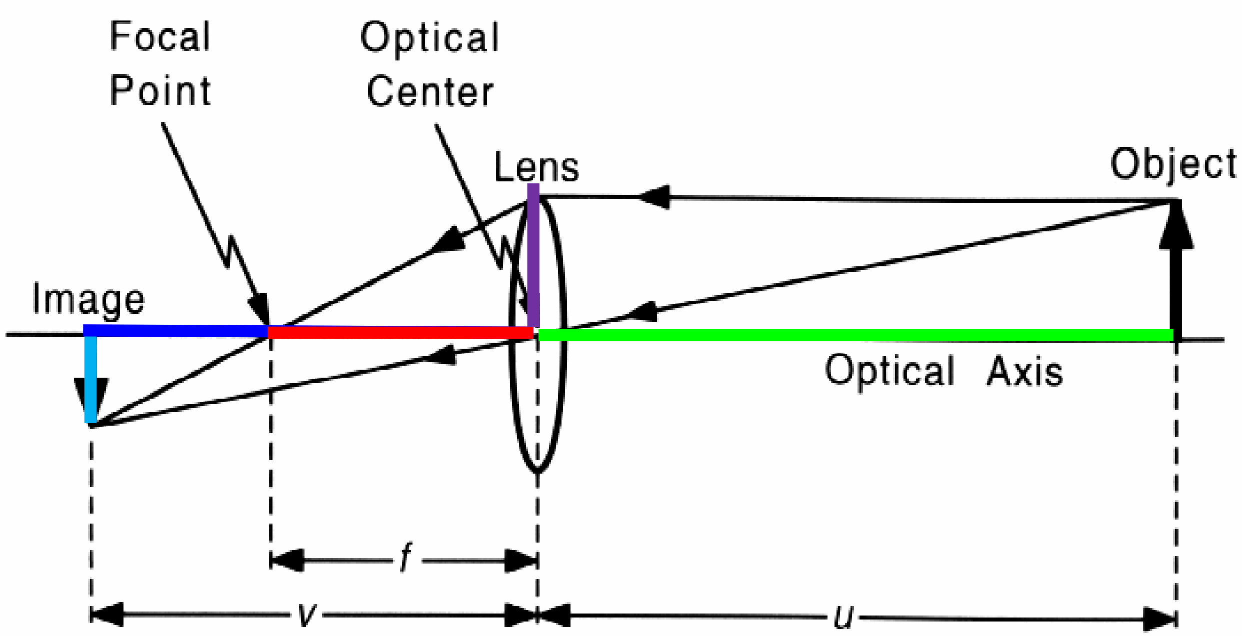
$\Rightarrow$ small Aperture

$\Rightarrow$ few light

- „thin" lense: small aperture but much light
- Thin lens law:

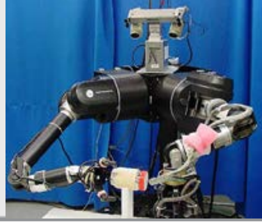
$$\frac{y_0}{y_i} = \frac{u}{v}$$

$$\frac{y_0}{y_i} = \frac{f}{v-f}$$

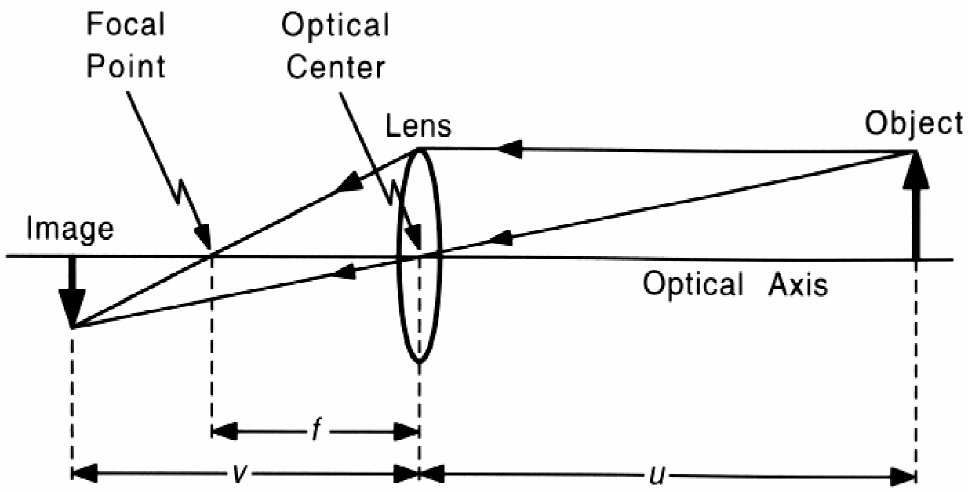


Thin-Lens Equation: $\frac{1}{u} + \frac{1}{v} = \frac{1}{f}$

Lenses

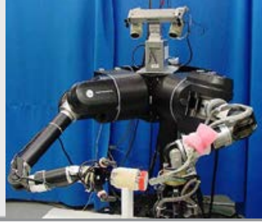


- **f: focal length** = distance of the point on the optical axis where all rays emerging from infinity meet to the lens plane (= all rays are parallel to the optical axis)
- if u = ∞ then v = f
- Rays going through the optical center of the lens are **not diffracted**
- **Field of view**: area that is recorded by a camera:
  - The bigger f the smaller the area that is imaged
  - Wide-angle - small f; Zoom - large f

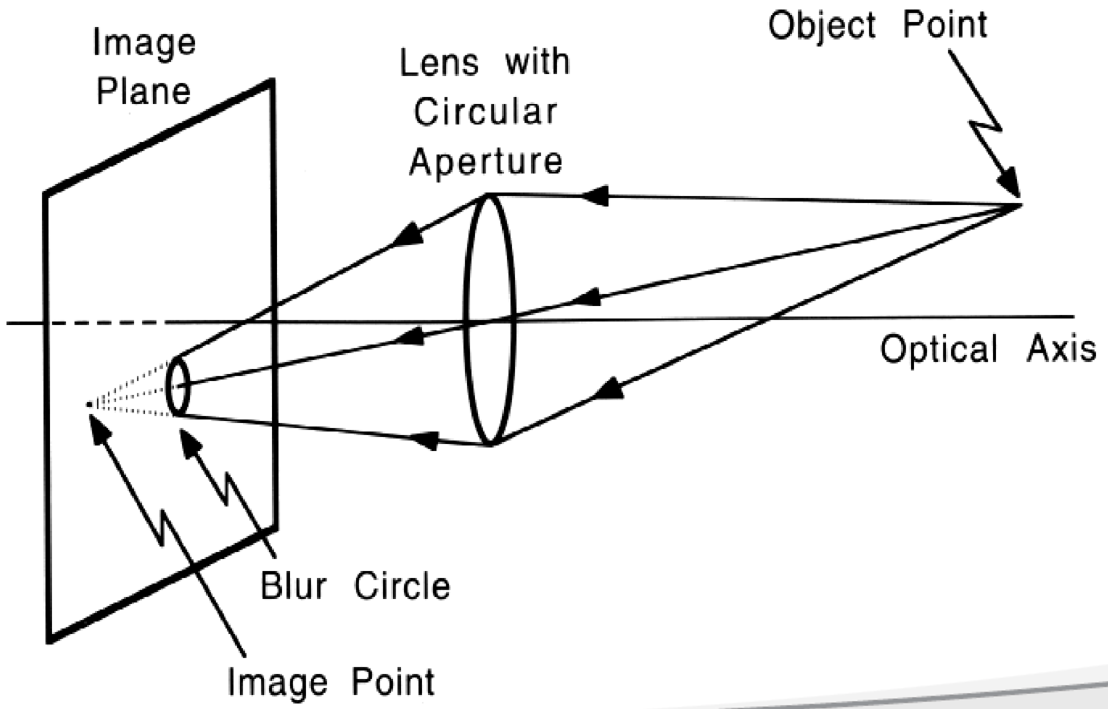


$$\frac{1}{u} + \frac{1}{v} = \frac{1}{f}$$

Depth of Field

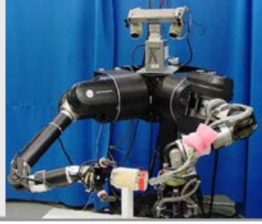


- Only objects in a certain distance are imaged sharply at the image plane, all other distances are blurred because of blur circles.
- The bigger the aperture, the bigger the blur circles
- The smaller the aperture, the sharper is the image



- ☐ The bigger the depth of field the darker the image
- ☐ Large Aperture = small depth of field

Depth of Field



- Same F/stop setting was used on all three lenses.
- Note the difference in depth of field.

Depth of Field

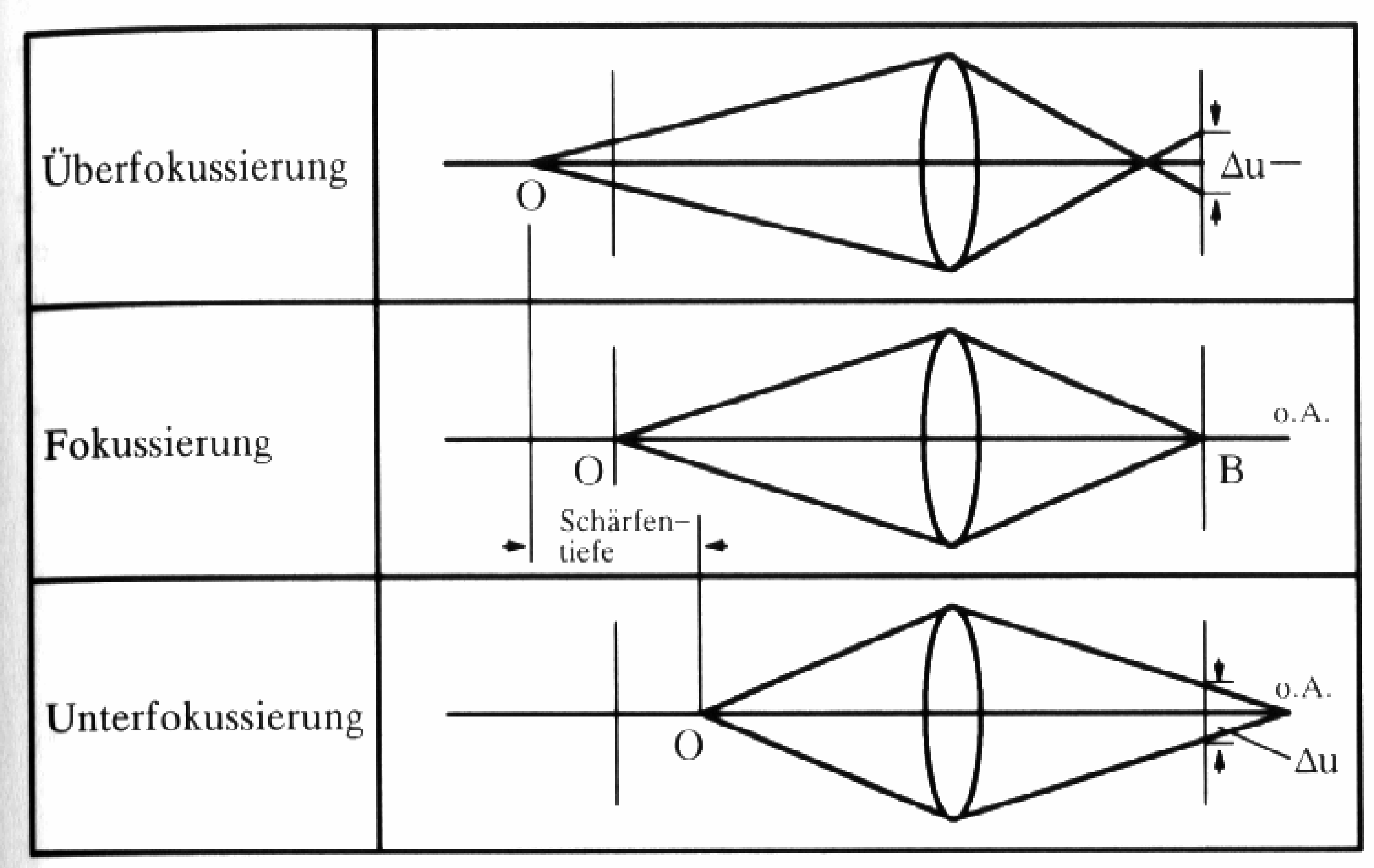
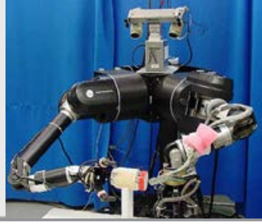


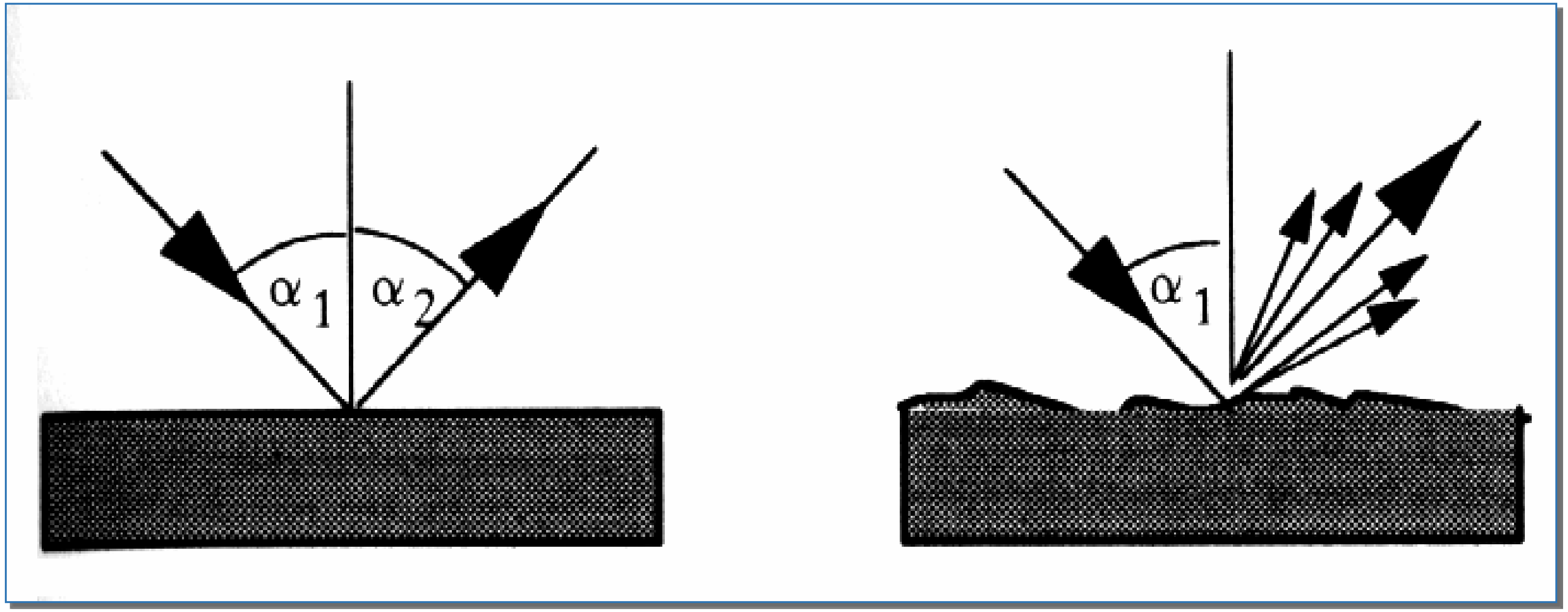
Image Generation

Radiometry

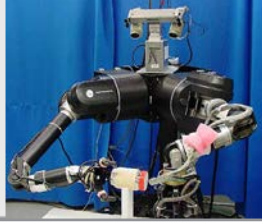


The radiometric relation between the world and its projection is formed by:

- Amount of light that is reflected by a surface point = **Radiance**
- Amount of light that is projected from this point onto the image = **Irradiance**
- measured in watts per square meter *(W/m²),*



Smouth Surface   Rough Surface



Radiometric Resolution

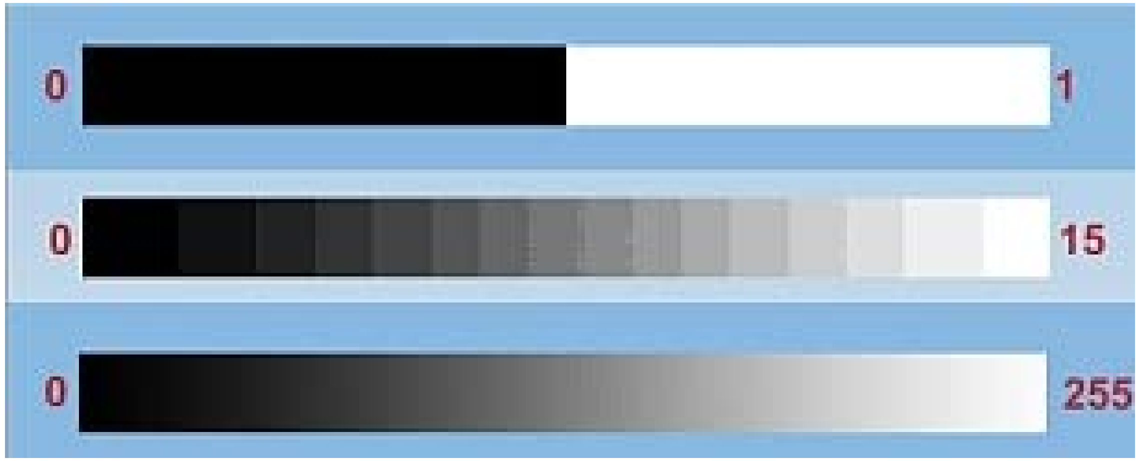
- Number of digital values ("gray levels") that a sensor can use to express variability of signal ("brightness") within the data
- Determines the information content of the image
- The more digital values, the more detail can be expressed
- Determined by the number of bits of within which the digital information is encoded

2^1 = 2 levels (0,1)

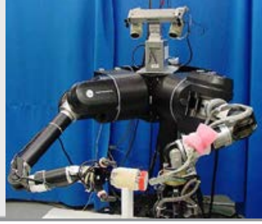
2^2 = 4 levels (0,1,2,3)

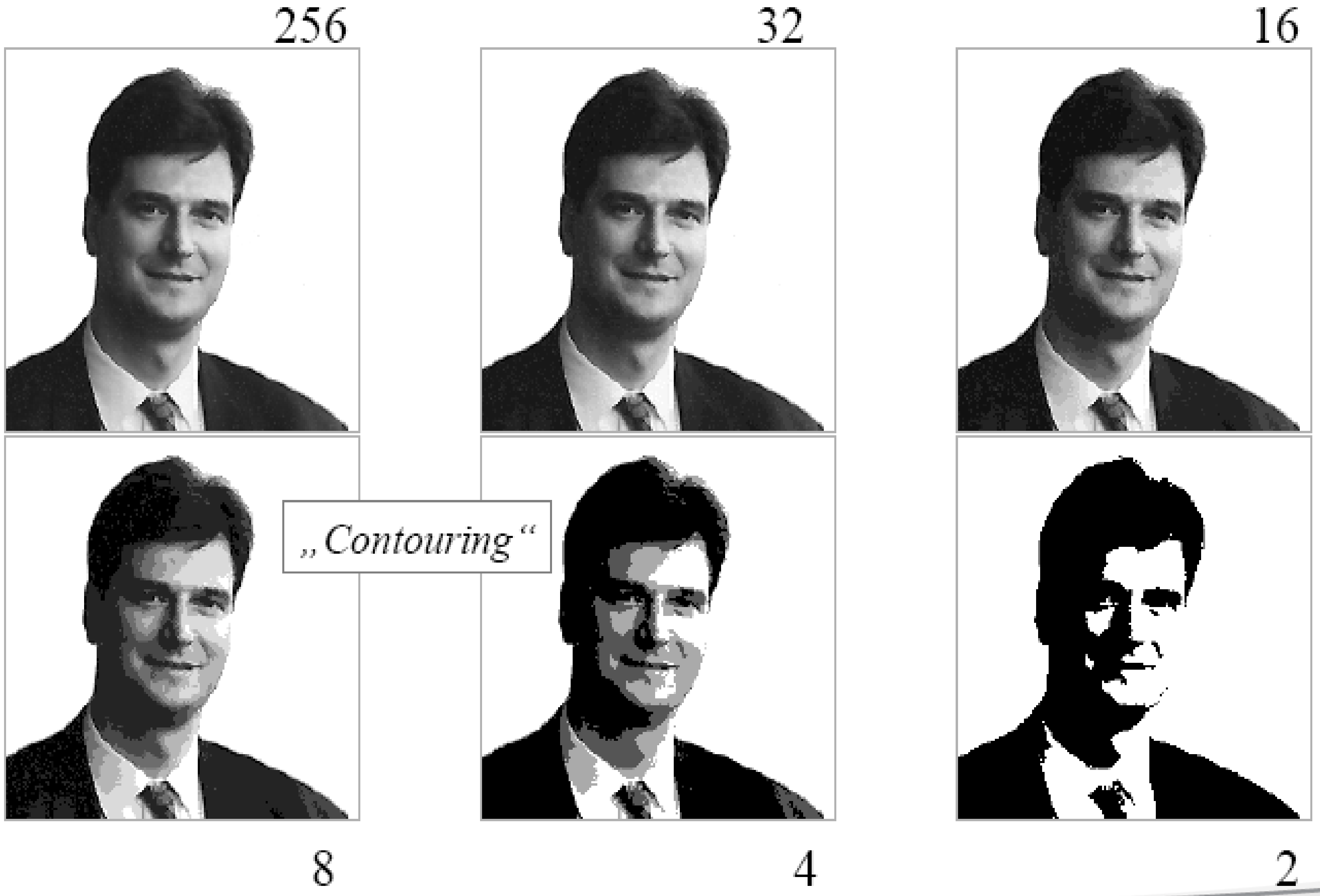
2^8 = 256 levels (0-255)

2^{12} = 4096 levels (0-4095)

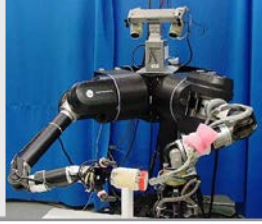


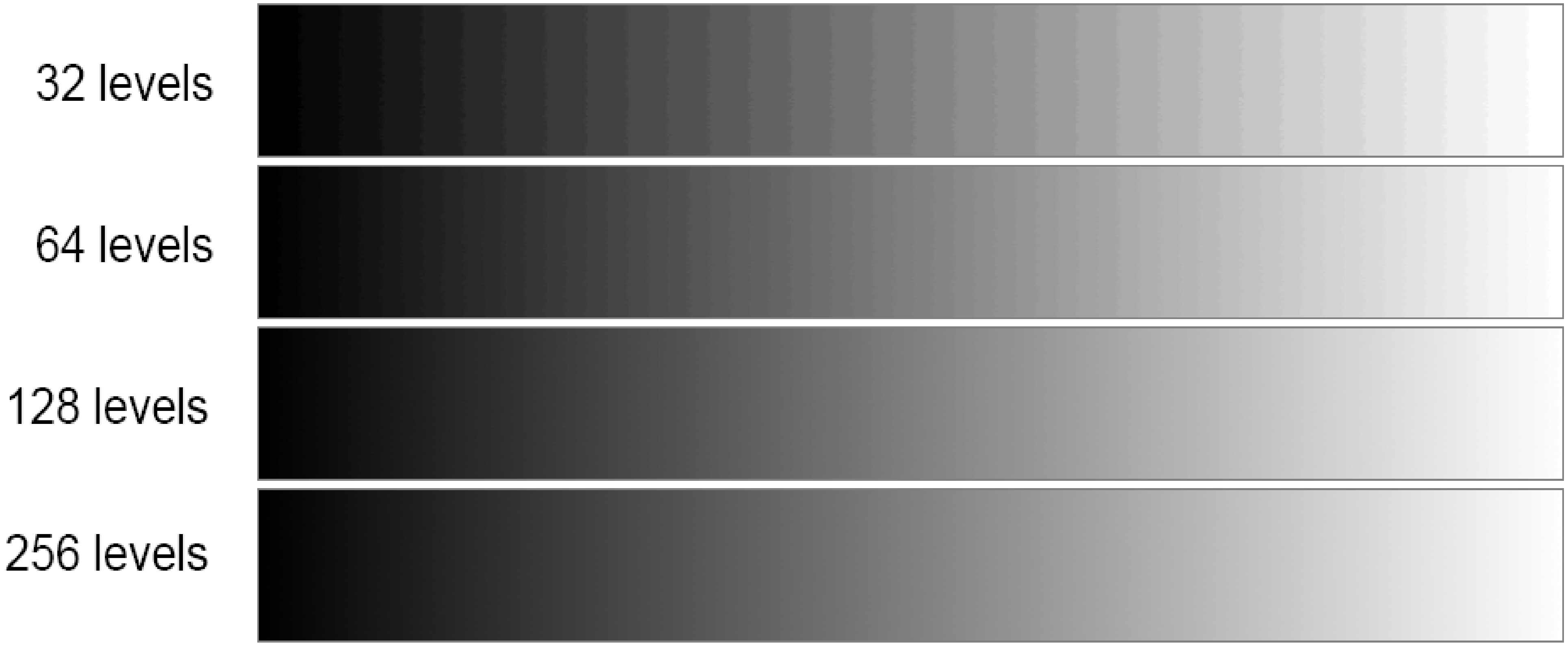
Different Numbers of Gray Levels





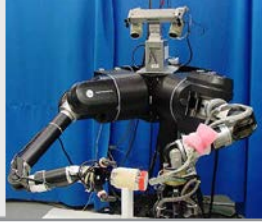
How Many Gray Levels are Required?

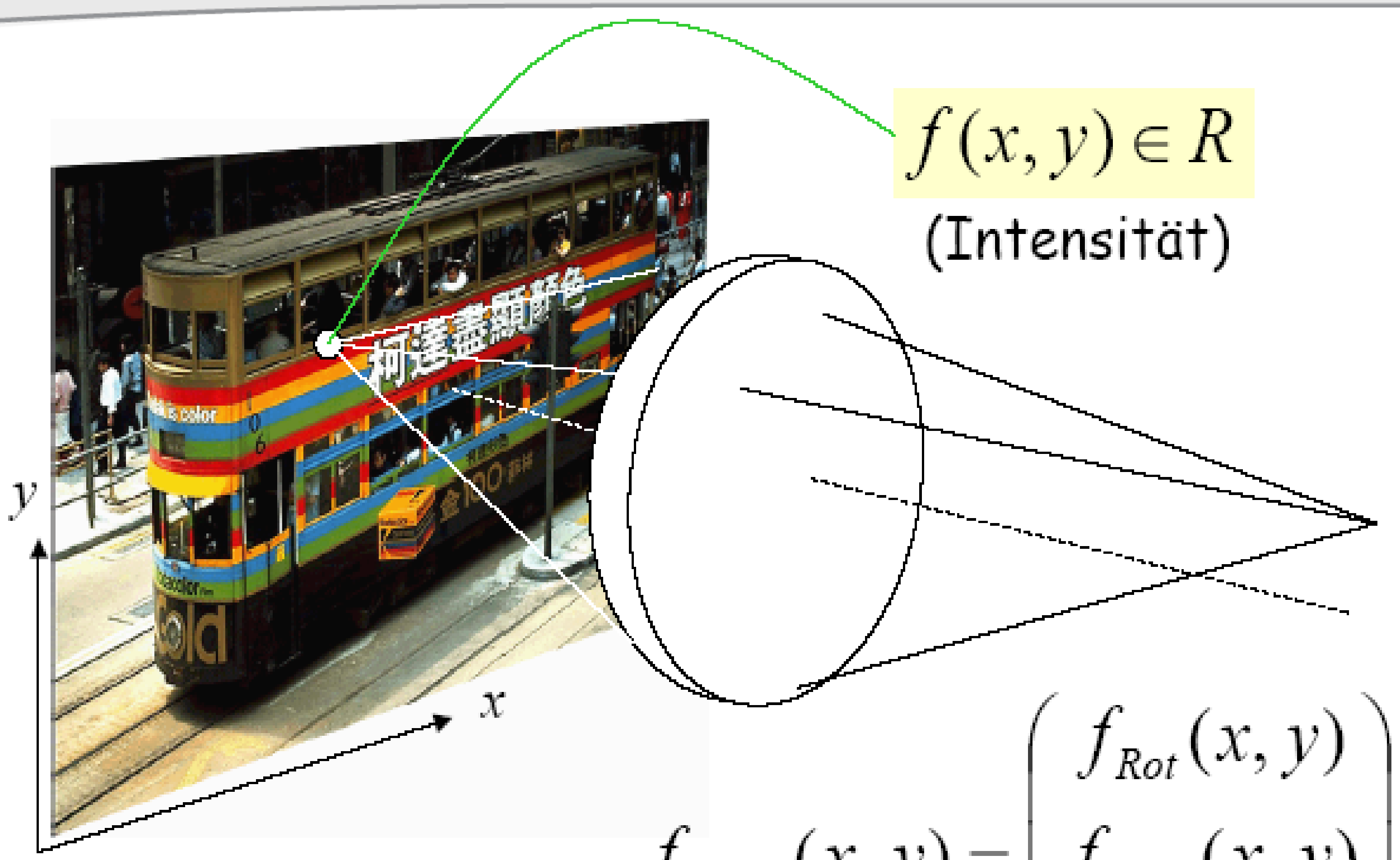




- Contouring is most visible for a ramp
- Digital images typically are quantized to 256 gray levels.

Continuous Image Function





$$f(x,y) \in R$$

(Intensität)

$$x, y \in R$$

$$f_{Color}(x,y) = \begin{pmatrix} f_{Rot}(x,y) \\ f_{Grün}(x,y) \\ f_{Blau}(x,y) \end{pmatrix}$$

(Farbe)

Transition to a Digital Image

50	23	7	9	
19	8	4		
6	10			

$f(x,y):$

$$R \times R \rightarrow R$$

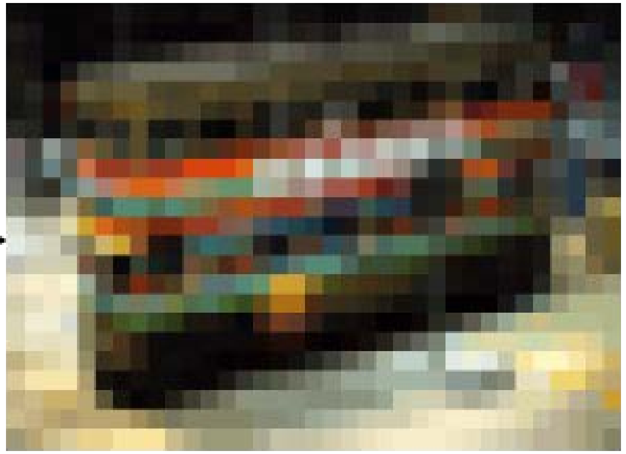
$g(u,v):$

$$Z \times Z \rightarrow Z$$

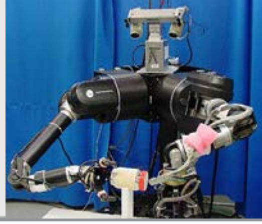
Transition to a Digital Image - 1

1. Räumliche Abtastung
(Sampling)

Sampler



Transition to a Digital Image - 2

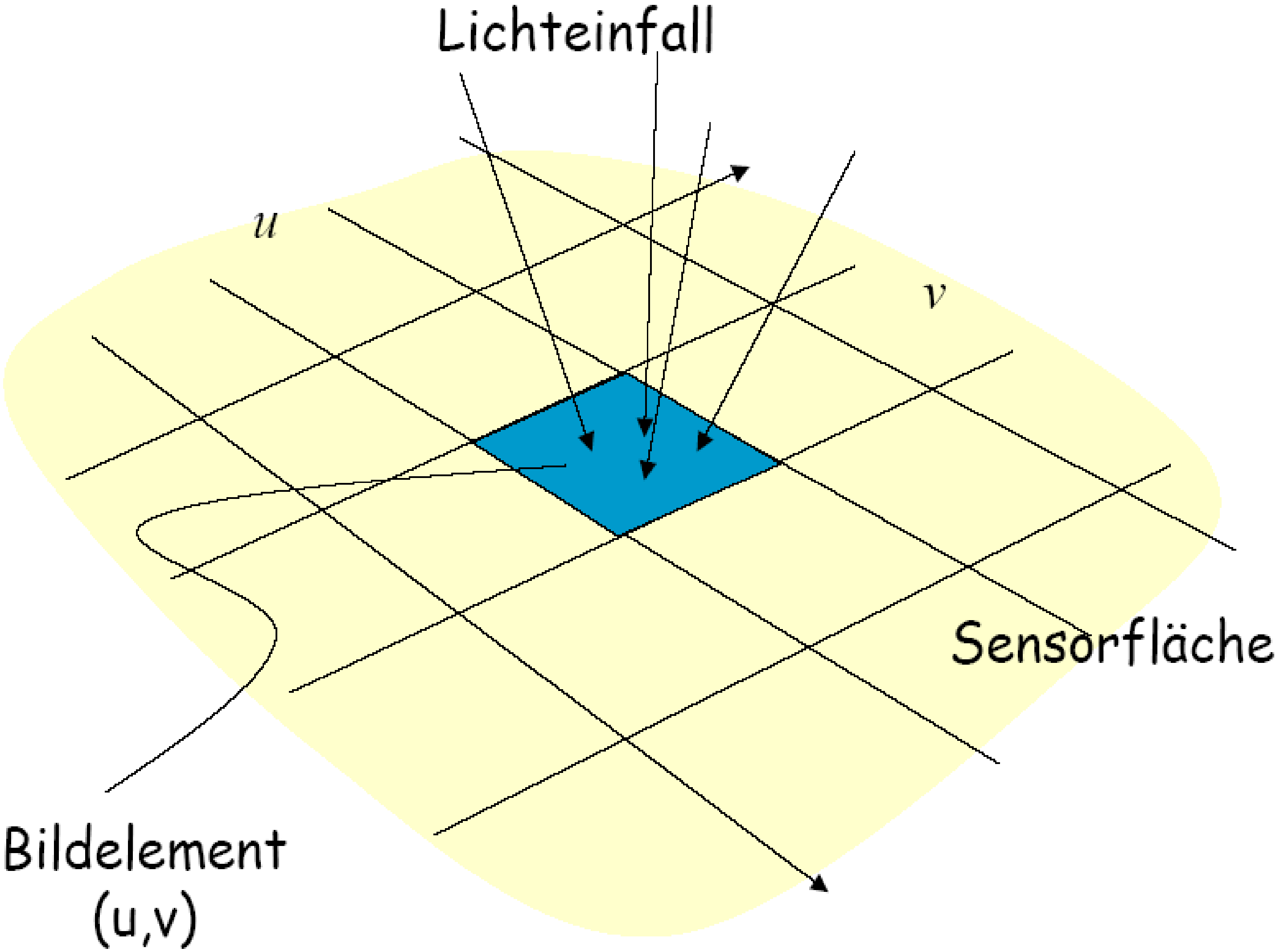


2. Diskretisierung der Bildwerte (Quantisierung)

Quantizer

50	23	7	9	
19	8	4		
6	10			

Spatial Sampling



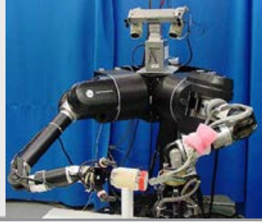
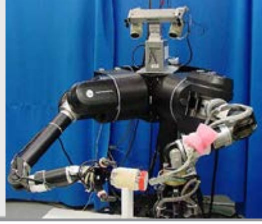
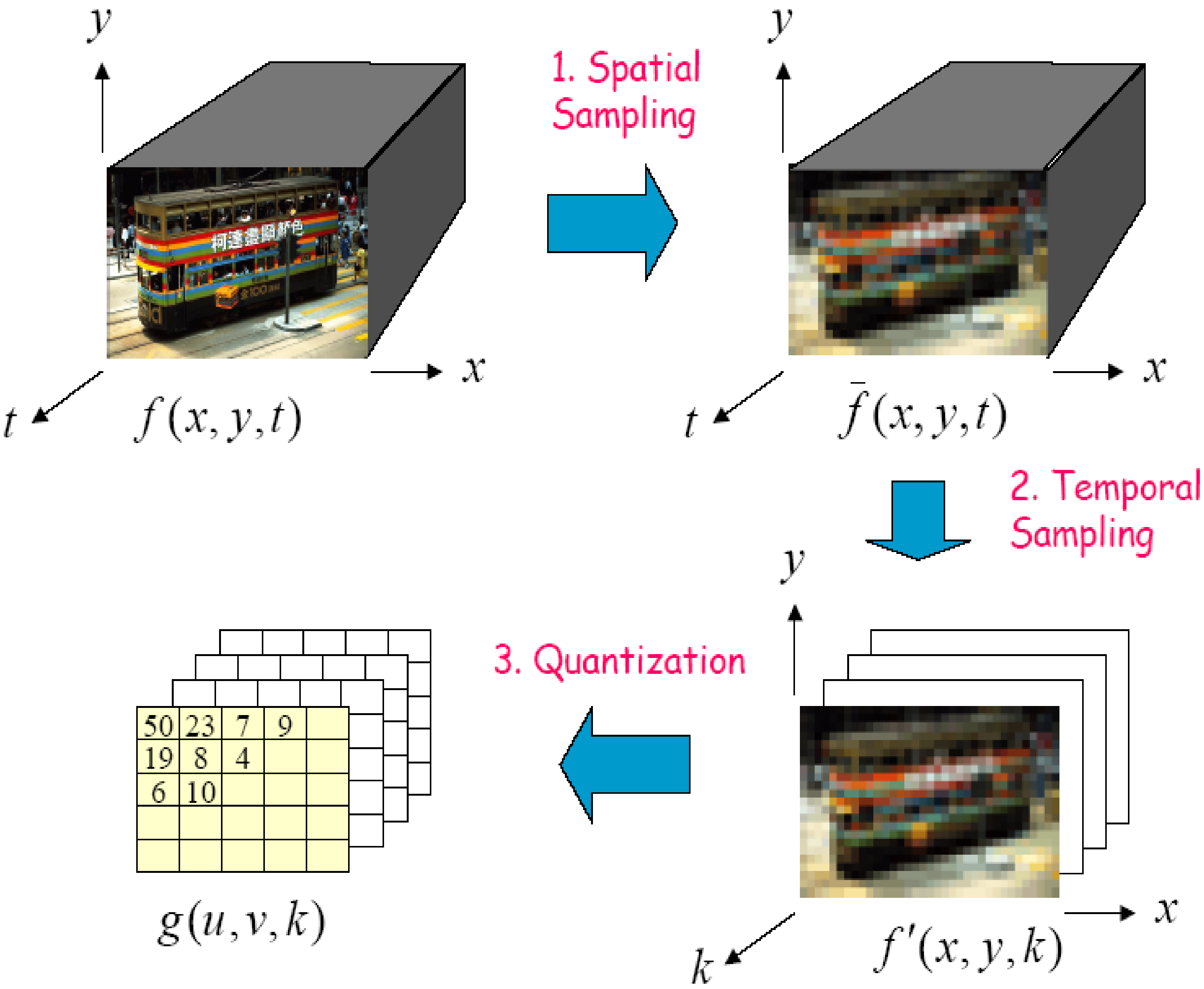


Image Size and Resolution

- These images were produced by simply picking every n-th sample horizontally and vertically and replicating that value nxn times:

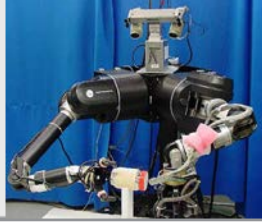
200x200 100x100 50x50 25x25



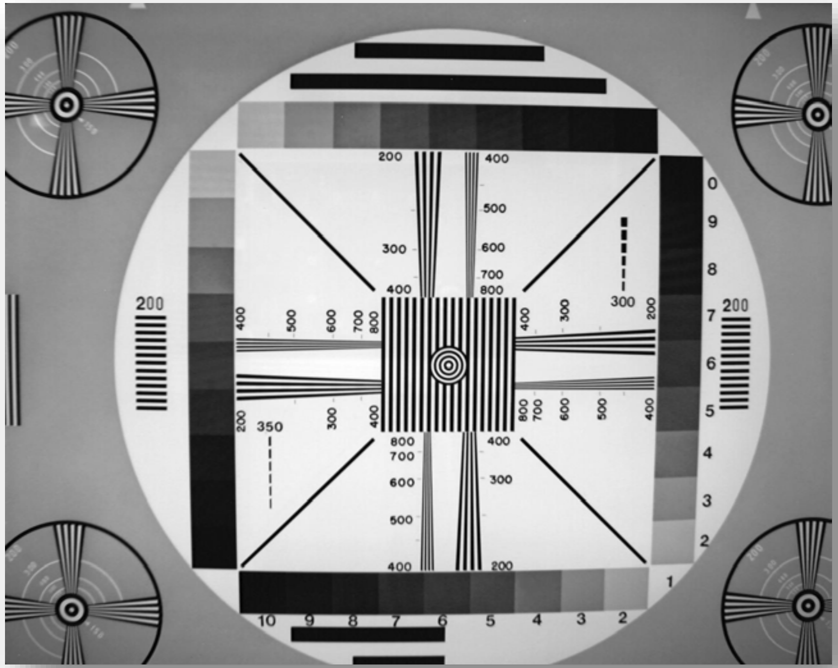


1. Spatial Sampling
2. Temporal Sampling
3. Quantization
$f(x,y,t)$
$\bar{f}(x,y,t)$
$f'(x,y,k)$
$g(u,v,k)$
x
y
t
k
50 23 7 9
19 8 4
6 10

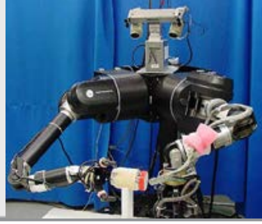
Spatial “Resolution” of a Sensor System



- **Spatial density** = Number of sensor elements (horizontal/vertical)
- **Optical resolution** = Quality of the optical system
- **Spatial resolution** = Relation pixel – object size (ppi)
- **Effective resolution:** Spatial density + Optical resolution (spatial resolution)



Signal Generation



Transformation of the optical image into an „electrical“:

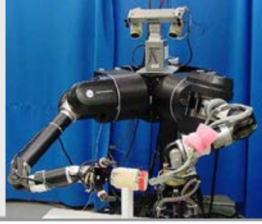
- Dependent on the wavelength:

$$E(x,y)=\iint Irrad(x,y,t,\lambda)\boxed{s(\lambda)}\boxed{\tau(t-t_0)}d\lambda dt$$

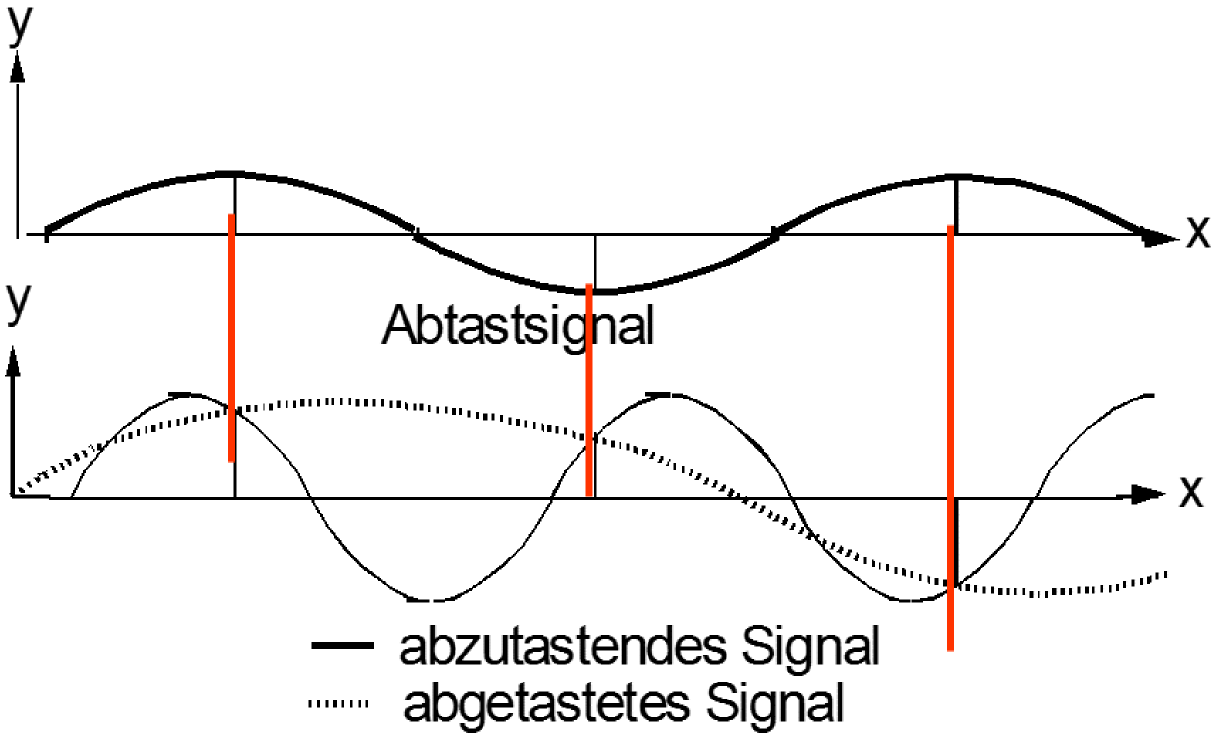
s(λ) = Spectral sensitivity of the sensor

τ(t) = timeframe of the acquisition at t = 0

Sampling Theorem



Shannon Theorem: Exact reconstruction of a continuous-time baseband signal from its samples is possible if the signal is bandlimited and the **sampling frequency** is **greater than twice the signal bandwidth**.

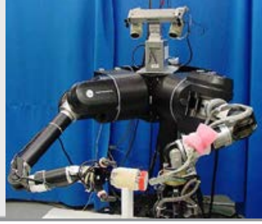


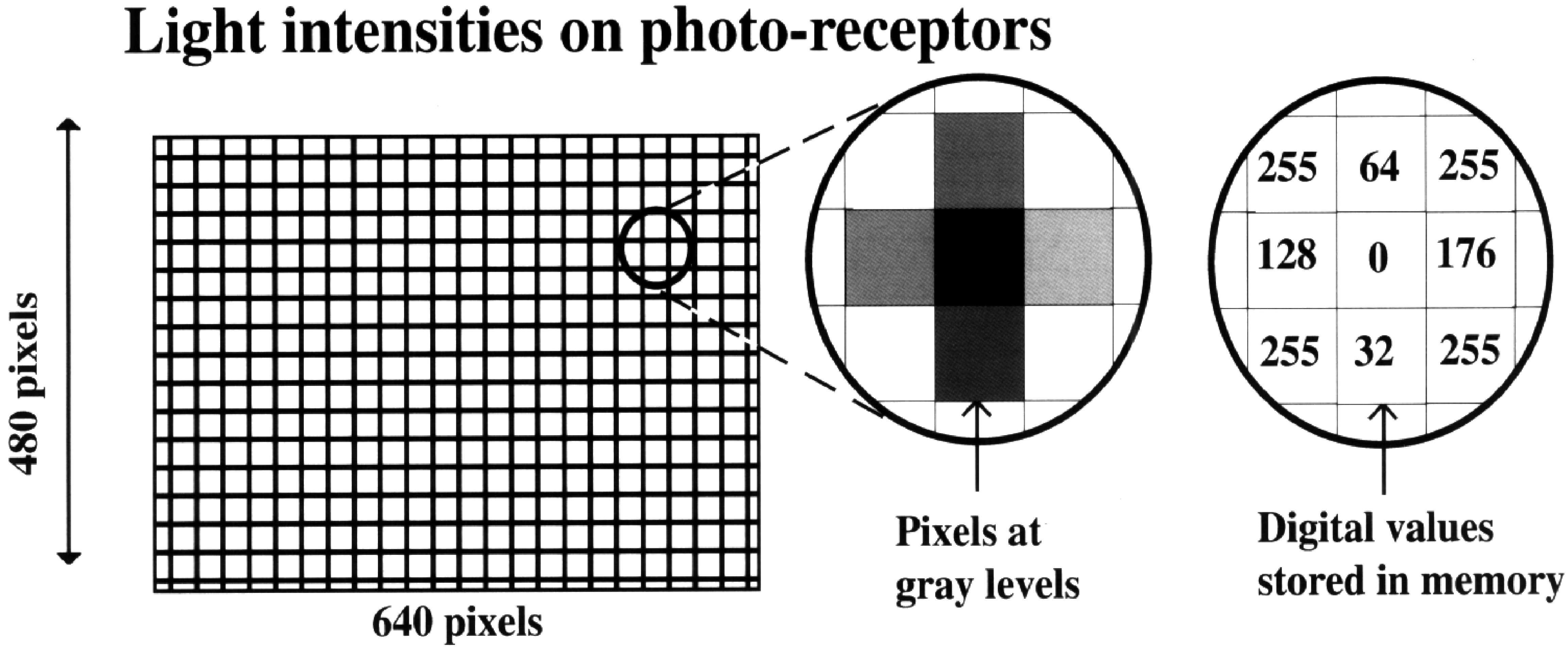
Sampling Theorem

- Is always valid!
  - Time
  - Space
  - Greylevel / Color

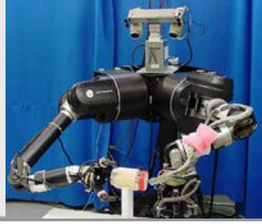
Sensors

Image Representation

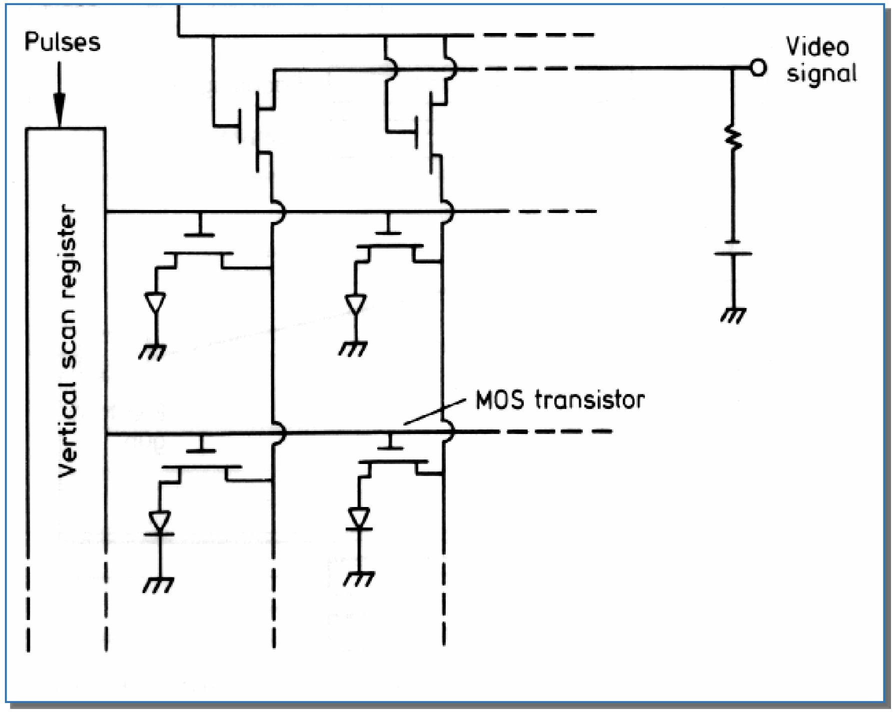




Cameras



- Mainly used class: **CCD Cameras**
- CCD = **C**harge **C**oupled **D**evice
- **MOS Transistors**, that charge themselves while light is projected



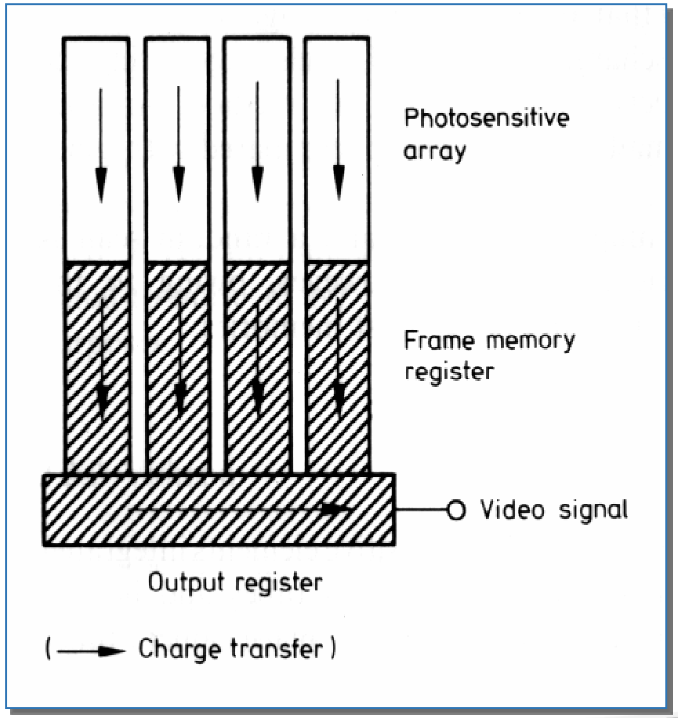
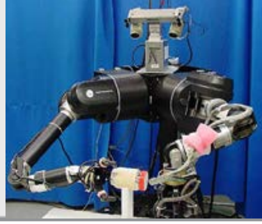


Image Scanning



- Path from the transistor of the camera to the A/D converter
- Image is read out line by line

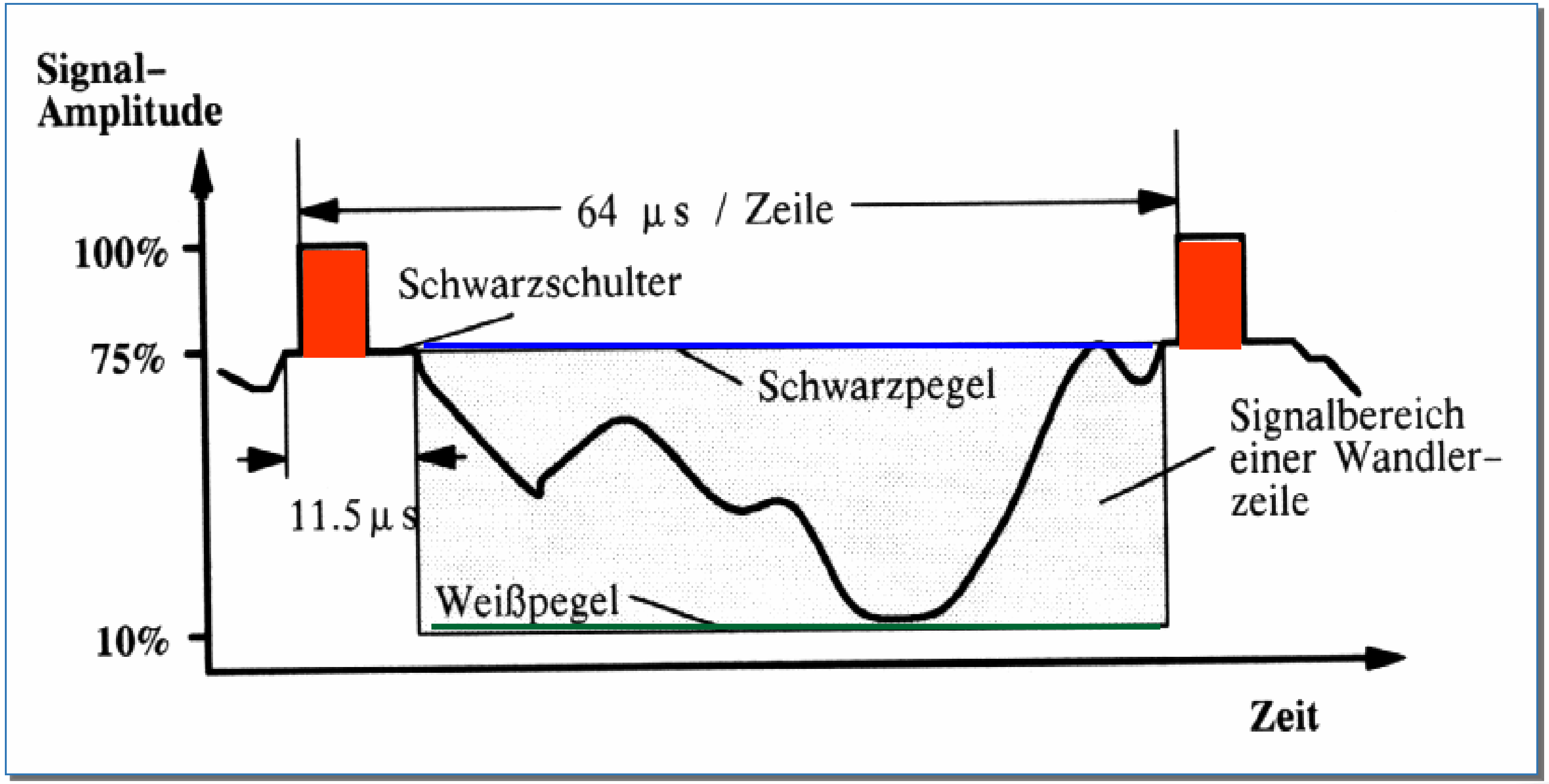
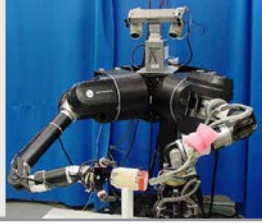


Image Scanning



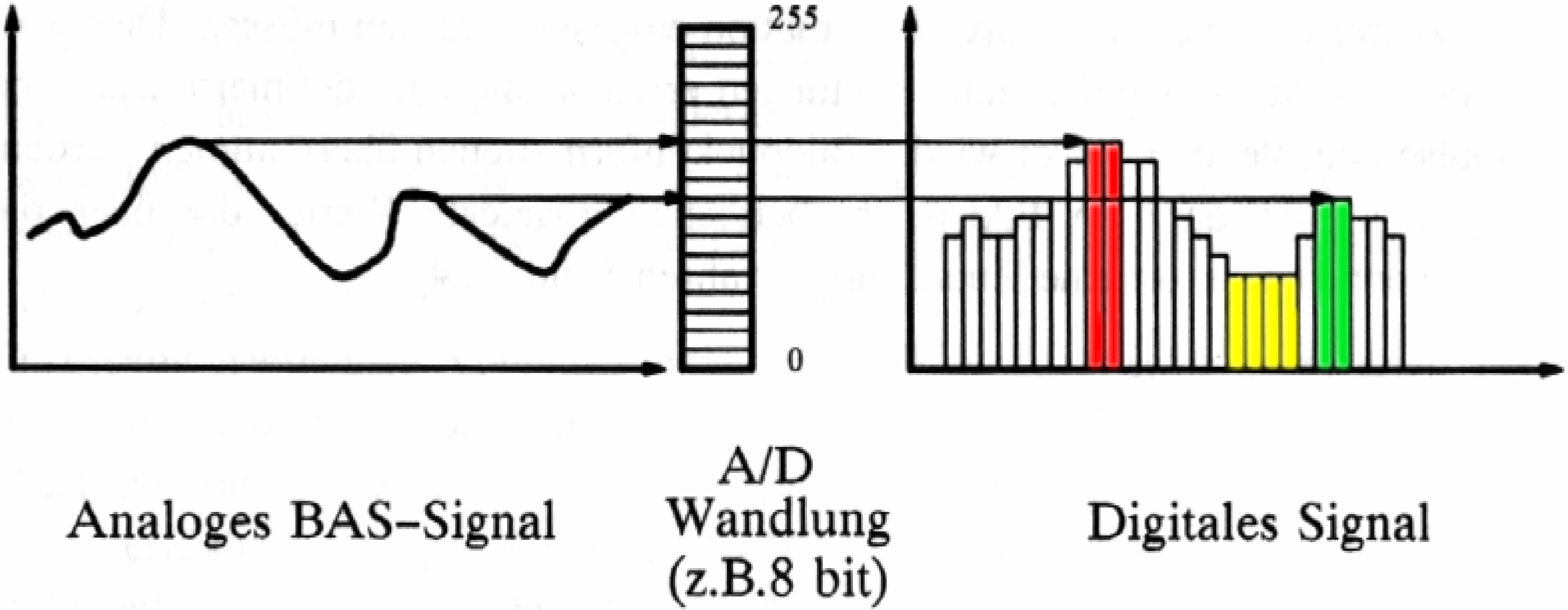
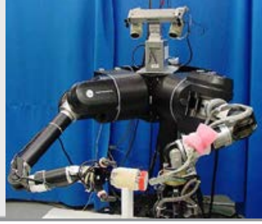


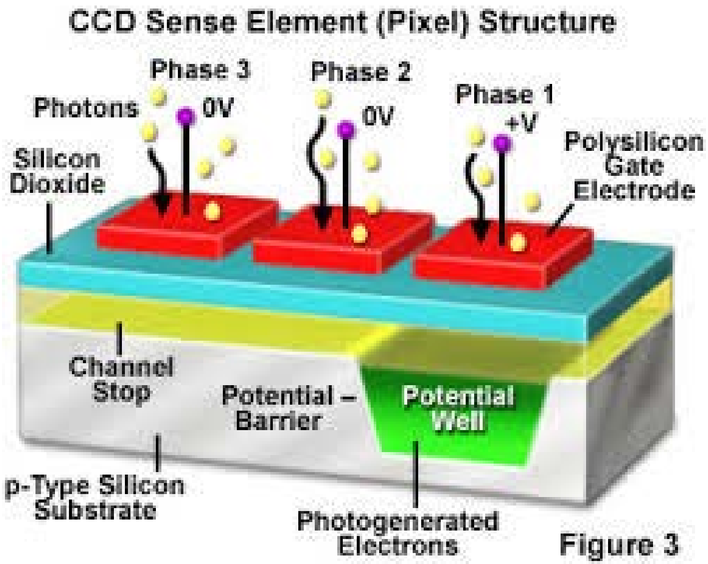
Image Sensors

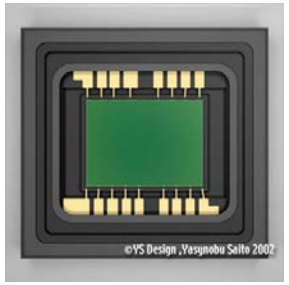


- Convert light into electric charge

■CCD (Charge Coupled Device)

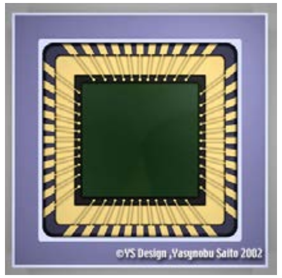
Higher dynamic range
High uniformity
Lower noise

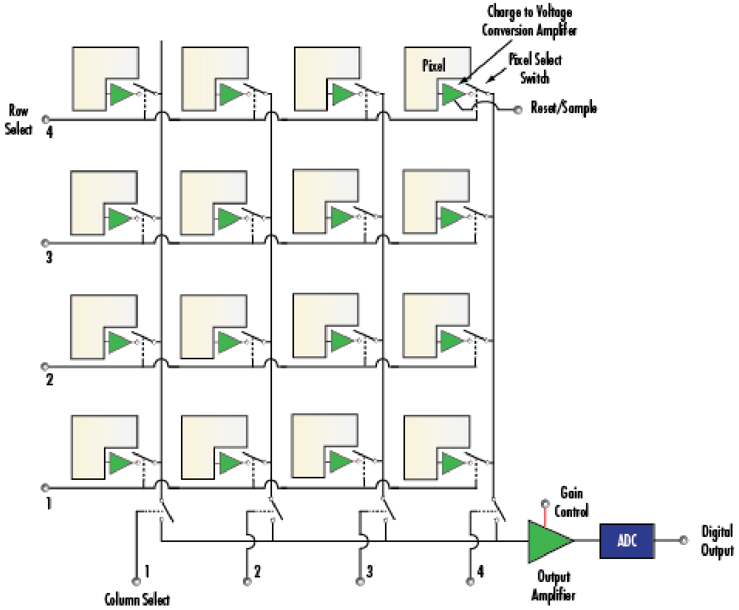




■CMOS (Complementary Metal Oxide Semiconductor)

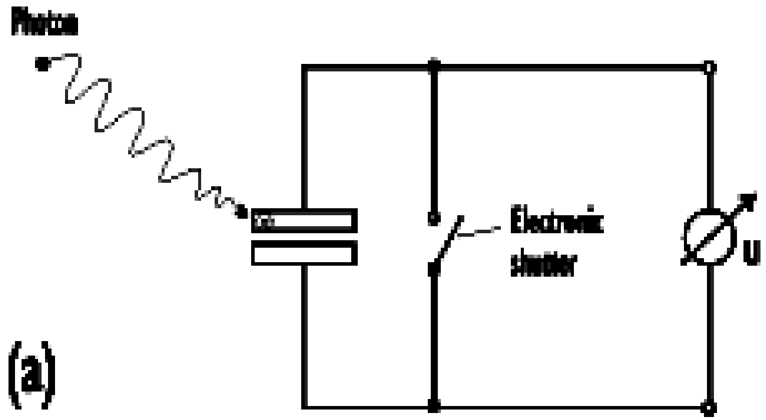
Lower voltage
Higher speed
Lower system complexity



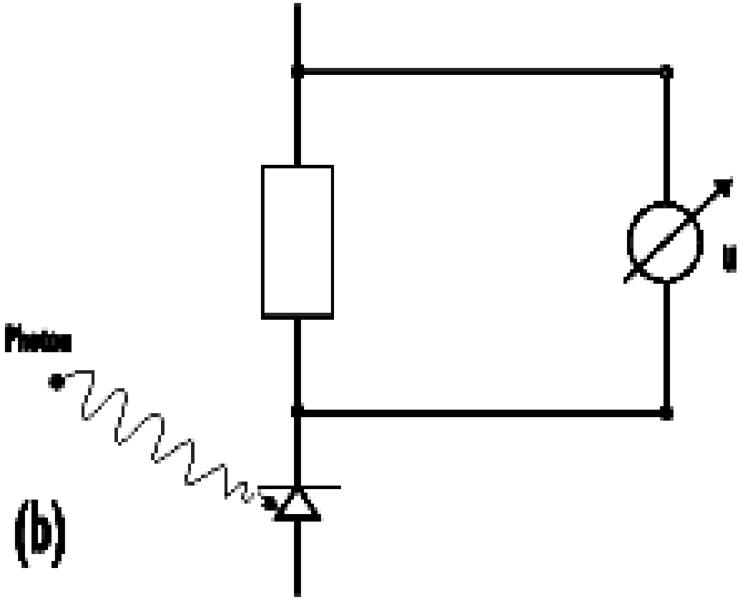


Charging Models

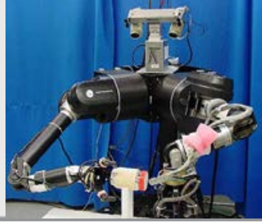
- CCD Cameras work **integrative**
- CMOS Cameras **non-linear**



Integrative/linear

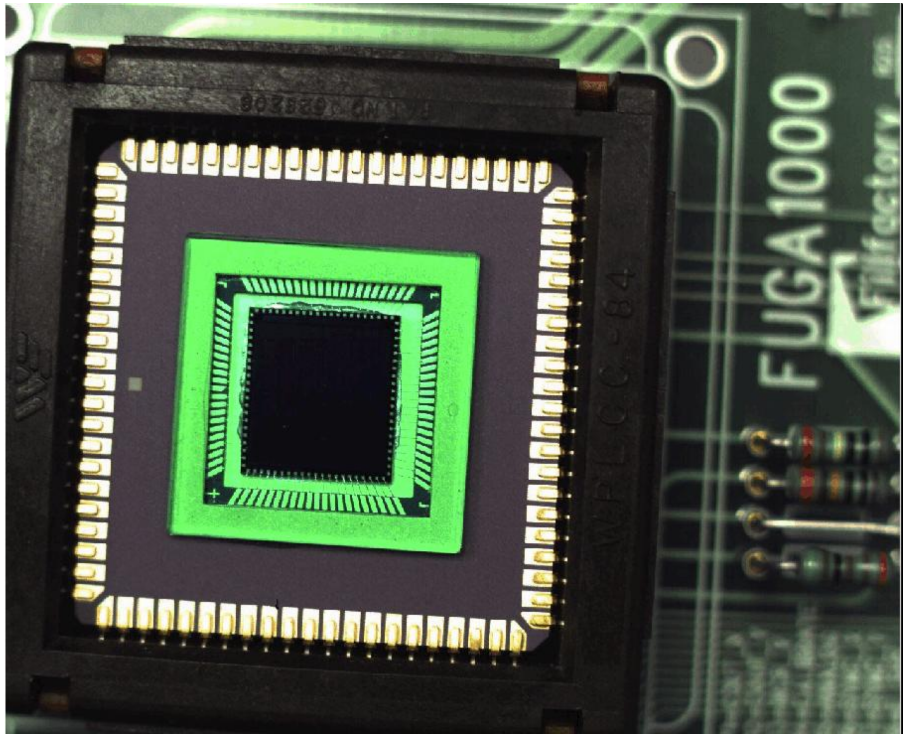


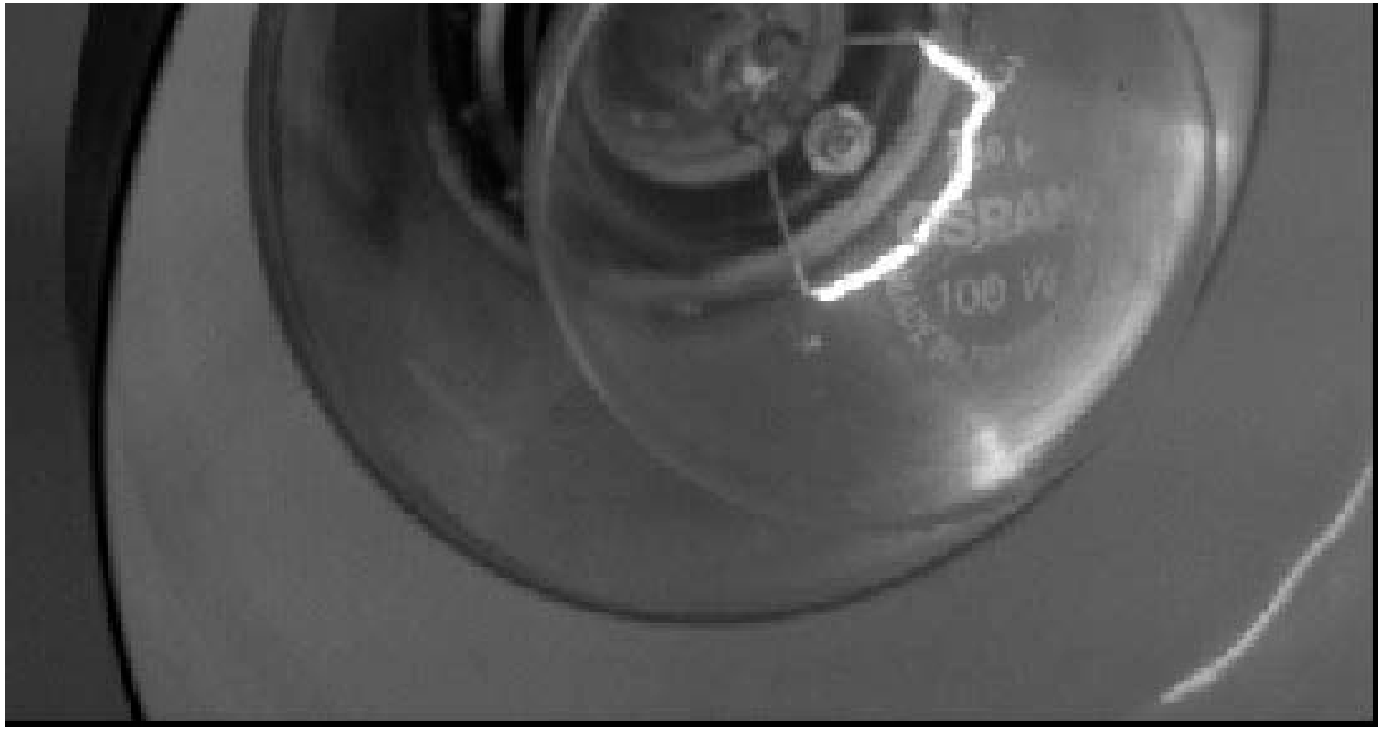
Non-linear



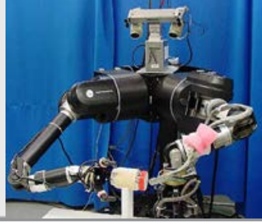
Example

- *Fuga 1000 Sensor:* *Image: log.Charge !!*





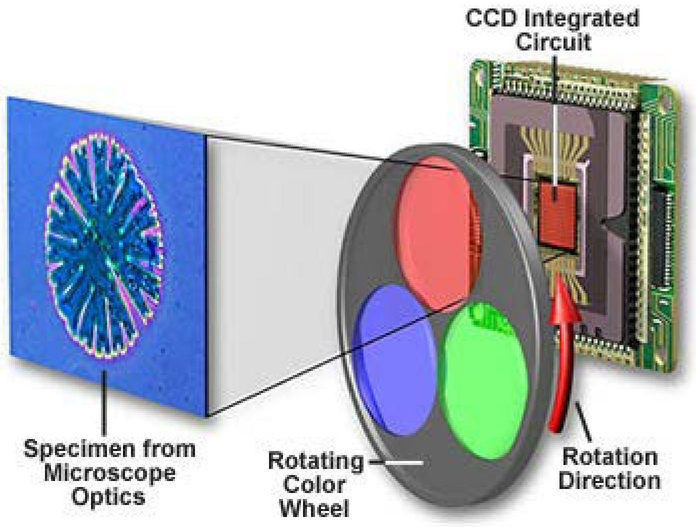
Types of Cameras

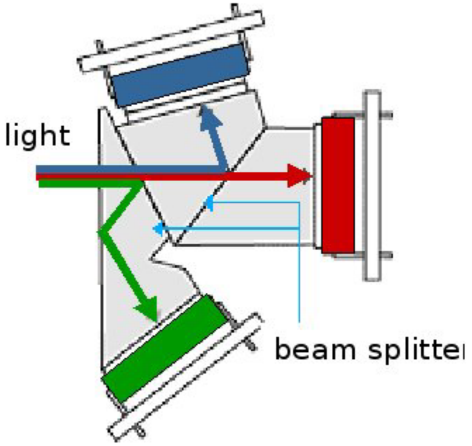


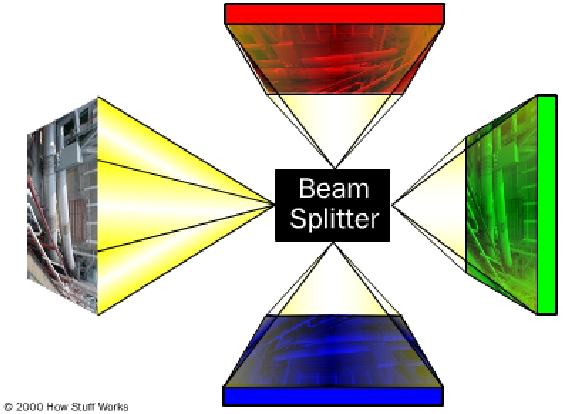
Color in Cameras

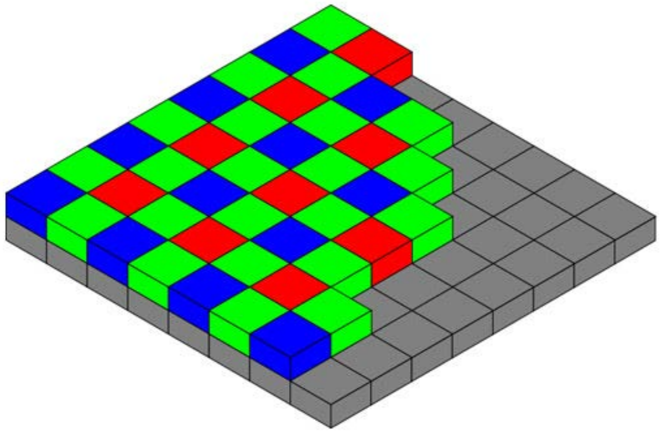
How CCDs Record Color

Sequential Color Three-Pass CCD Imaging System

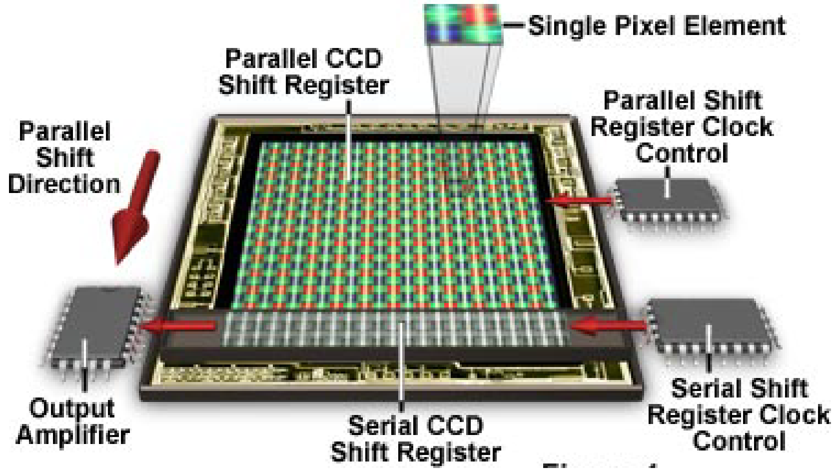




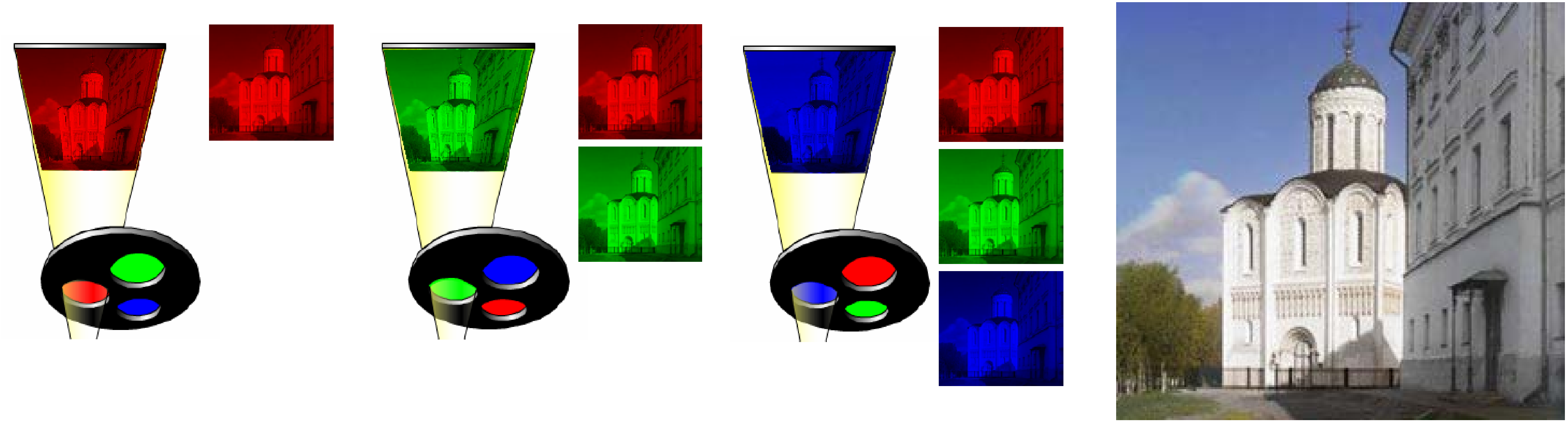




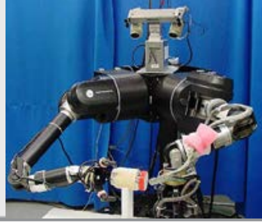
Full-Frame CCD Architecture

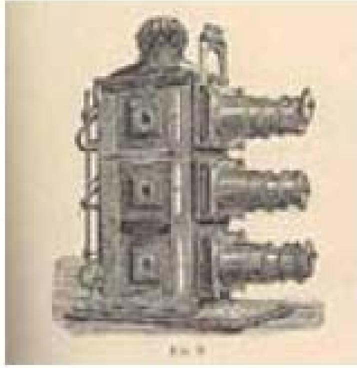


Field Sequential



Prokudin-Gorskii (early 1900's)

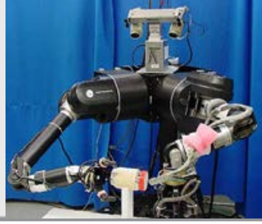


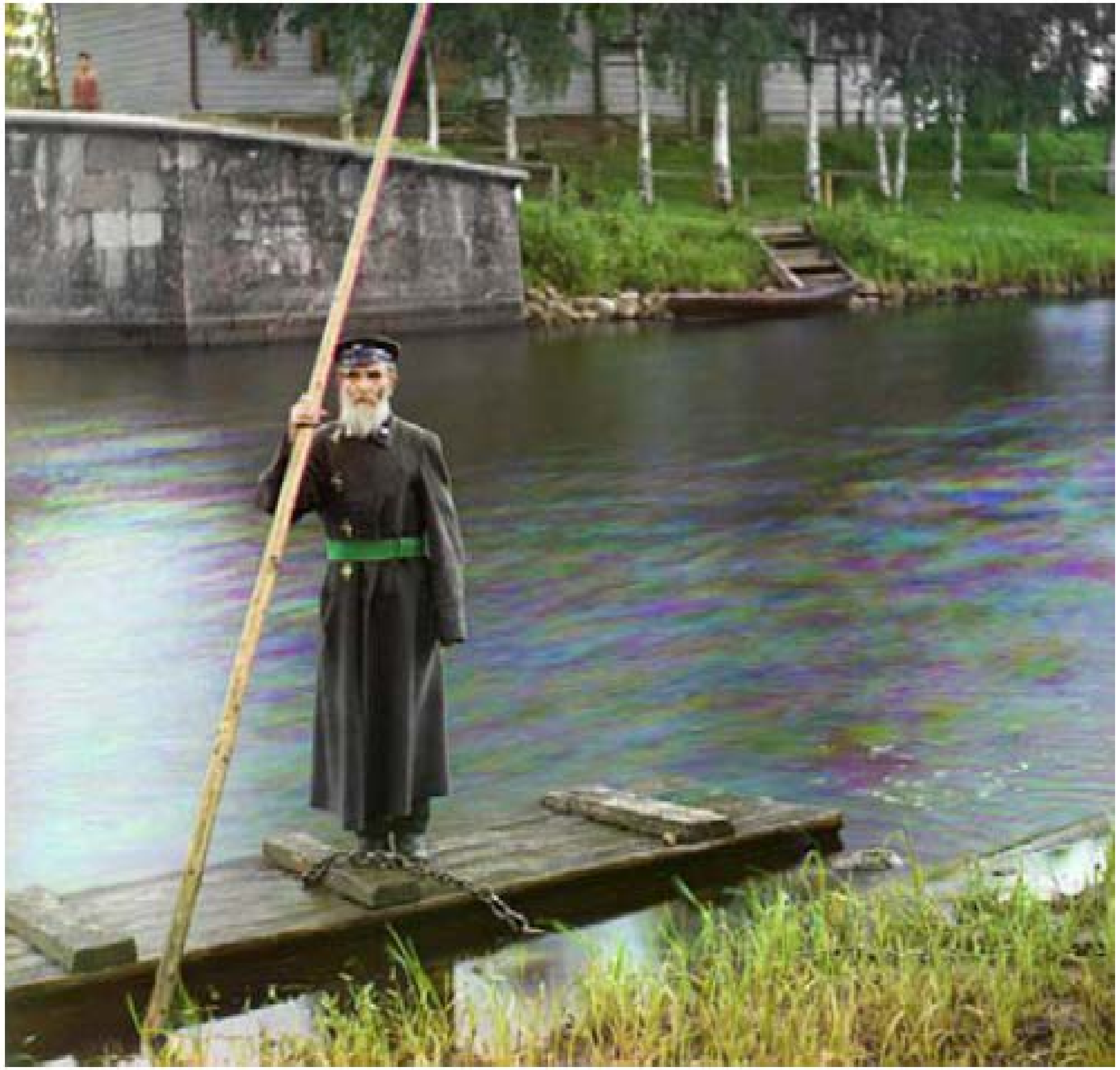


Lantern projector

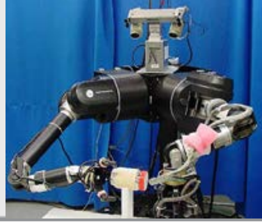
http://www.loc.gov/exhibits/empire/

Prokudin-Gorskii (early 1900’s)



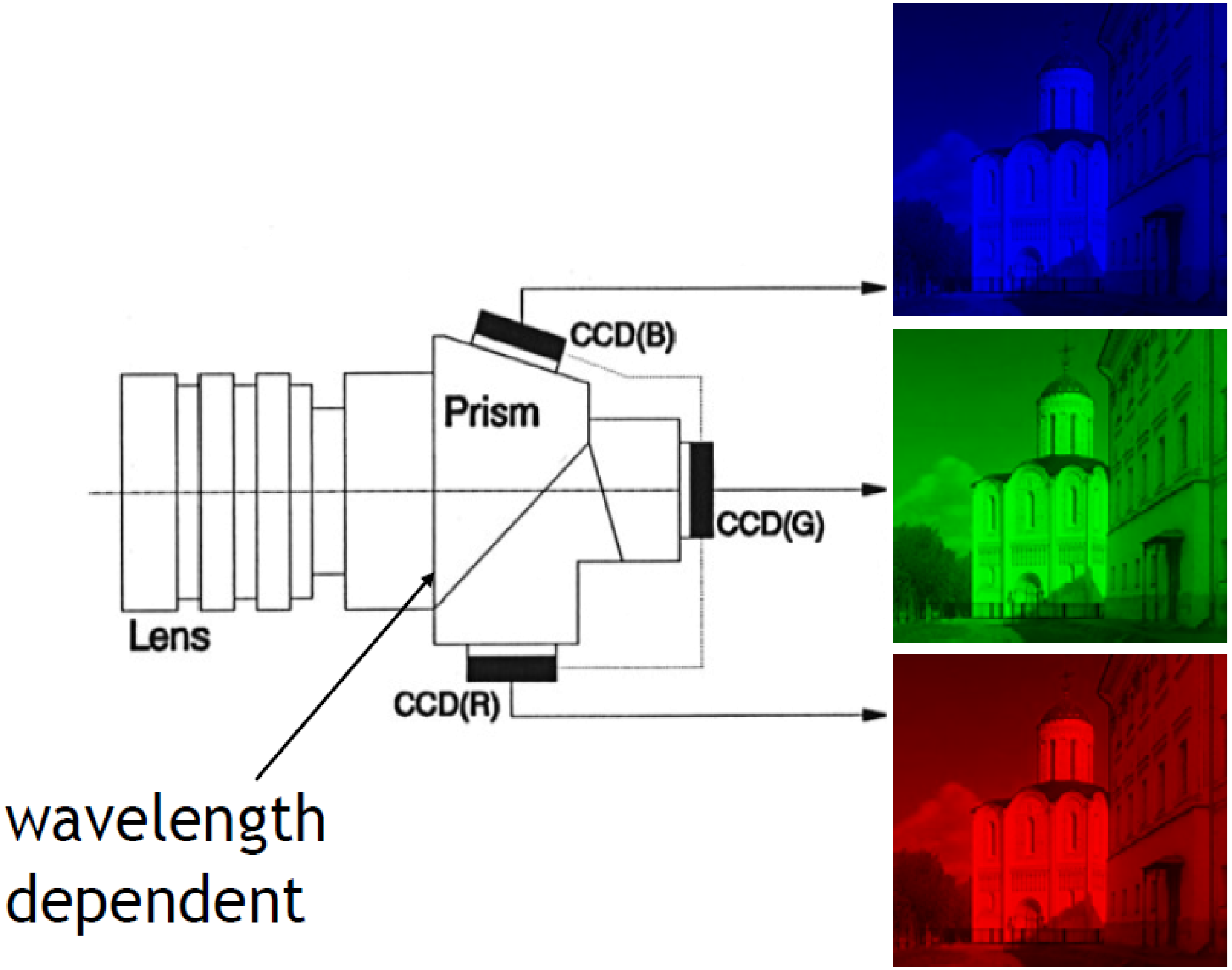


3-Chip Camera



- Accurate color per pixel
- Expensive
- 1/3 light per chip
- No DSLR cameras

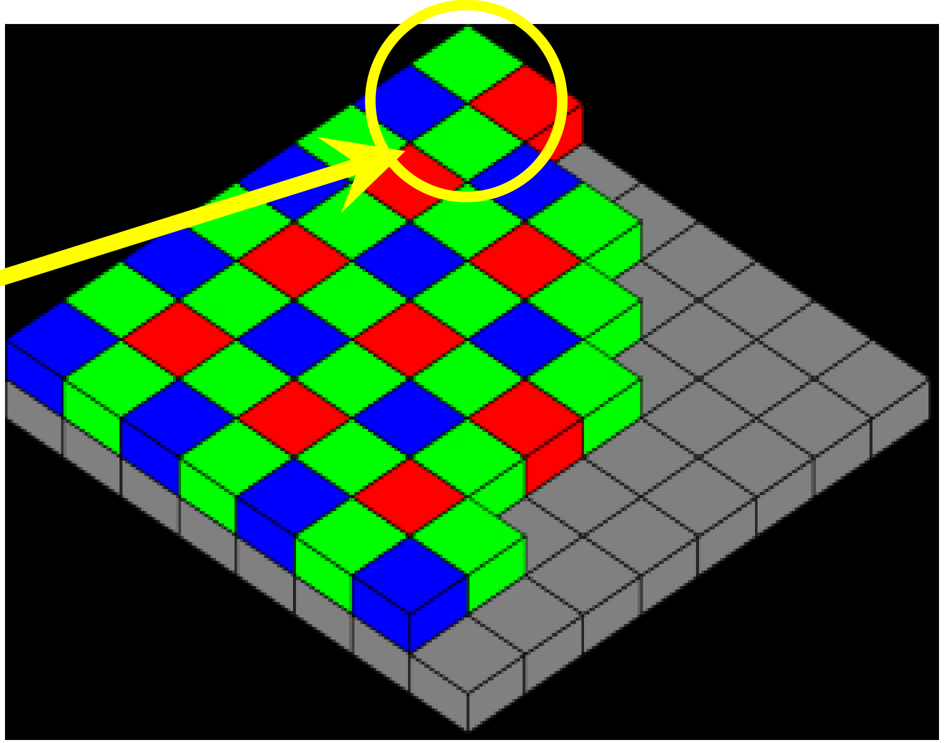
Sony DXC-D55PL



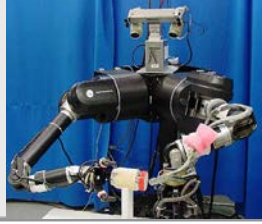
How CCDs Record Color

- Each CCD cell in CCD array produces single value independent of color.

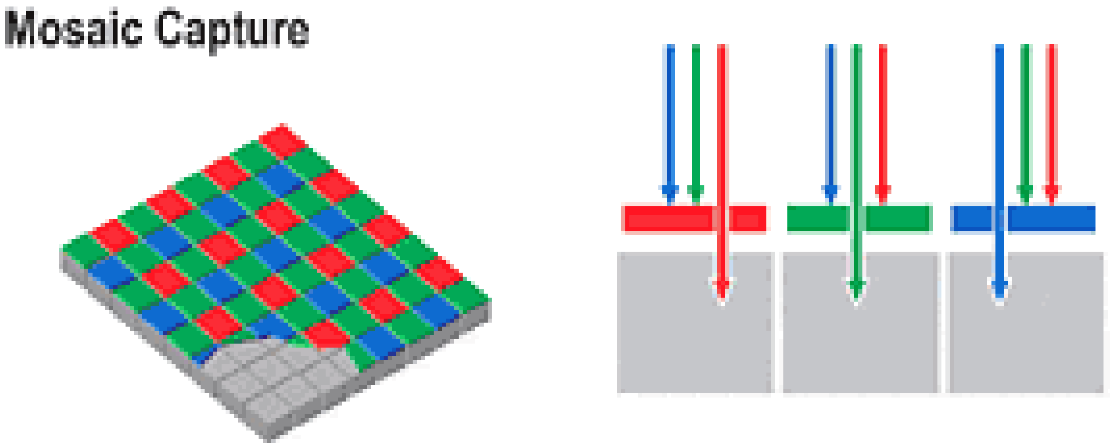
- To make color images, CCD cells are organized in groups of **four cells** and color filters are placed on top of the group to allow red, blue and green light to hit one of the four cells.

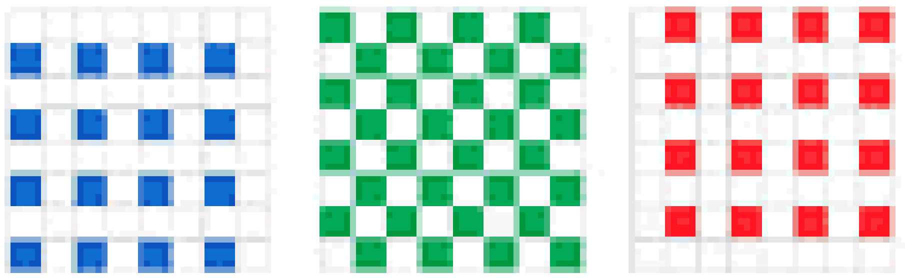


Bayer Filter

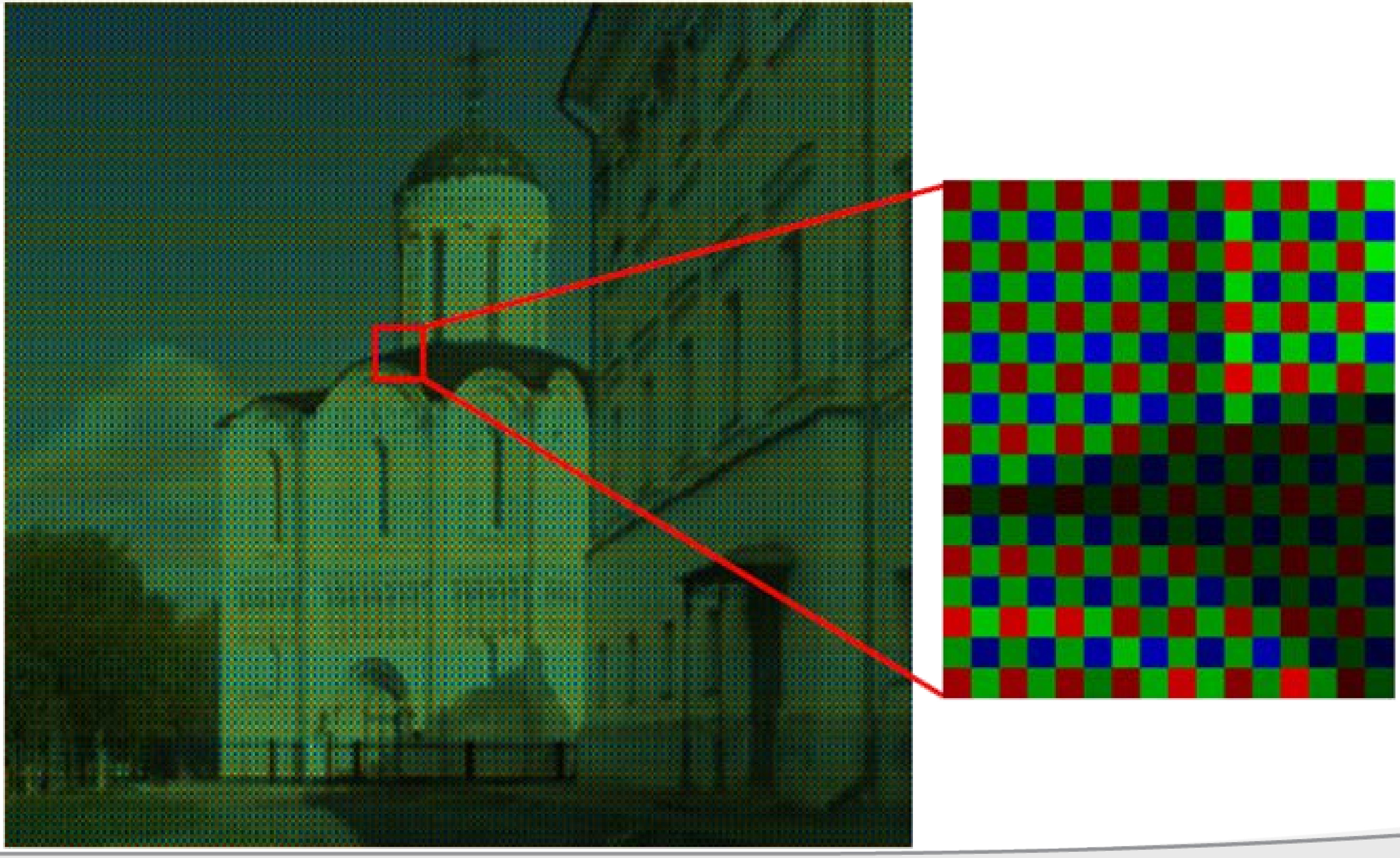


- **Specific arrangement** of a color filter array on a photo sensor due to B. E. Bayer.
- **Color pattern** has 50% green elements, 25% red and 25% blue, also referred to as RGBG or GRGB.
- Human eye has greater resolving power with **green light**.
- **Demosaicing algorithms** convert from Bayer color pattern to RGB by interpolating neighboring values.

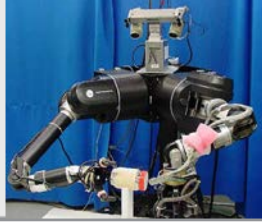




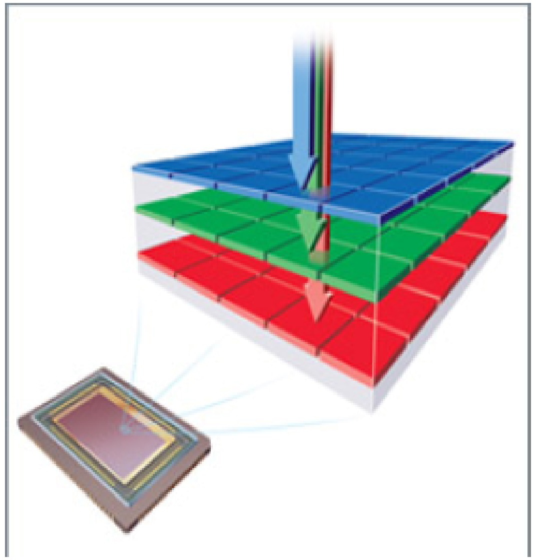
Bayer Filter

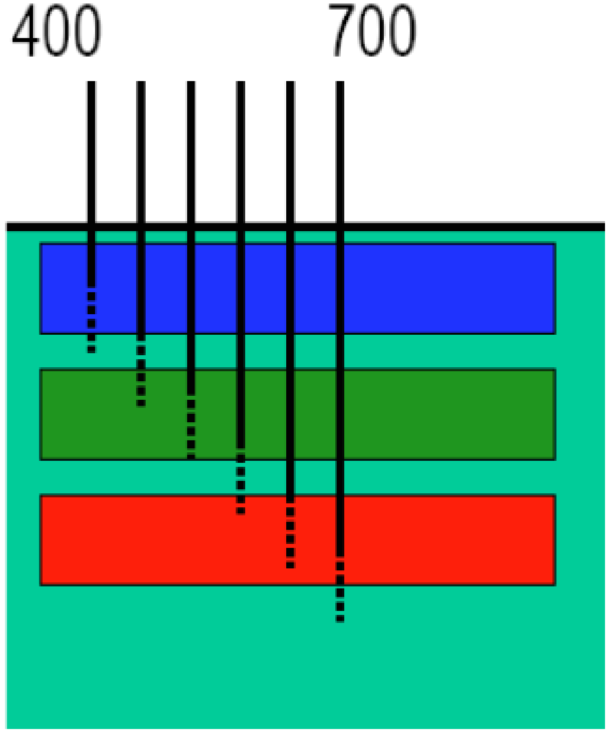


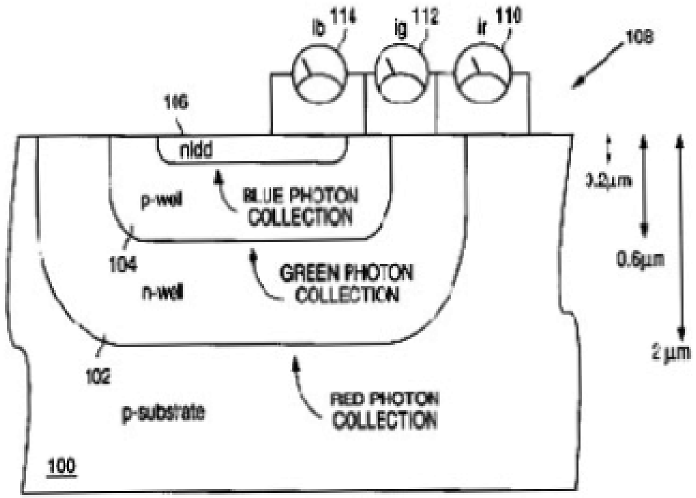
Foveon X3 Sensor



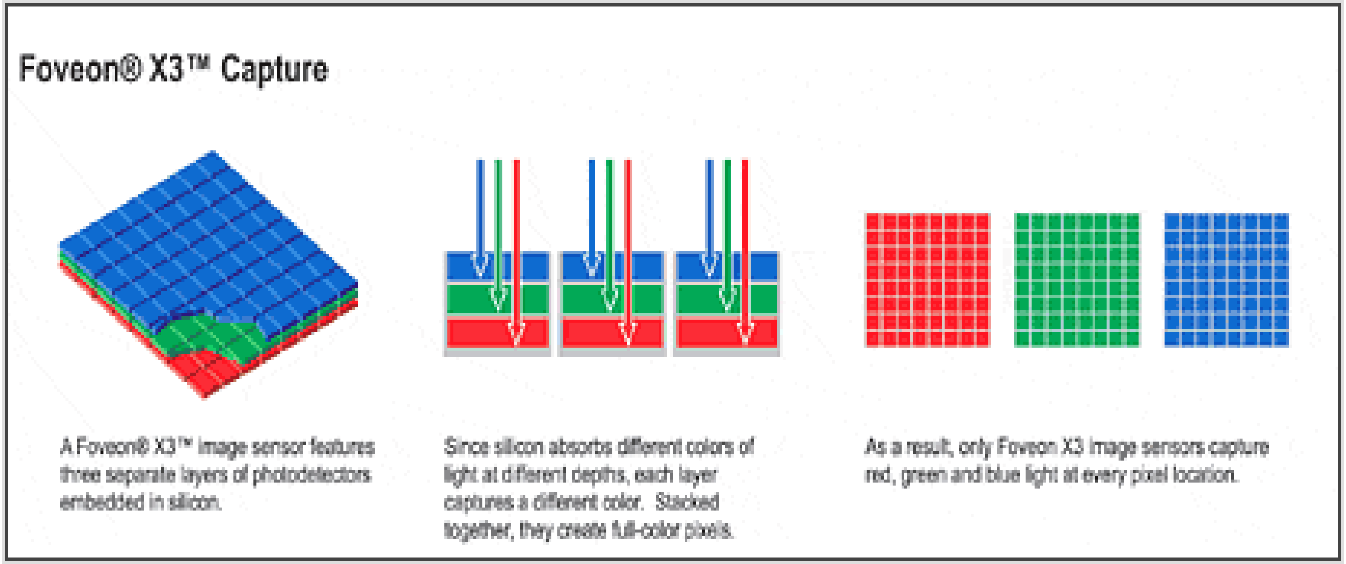
- Light penetrates to different depths for different wavelengths
- **Multilayer CMOS** sensor gets 3 different spectral sensitivities

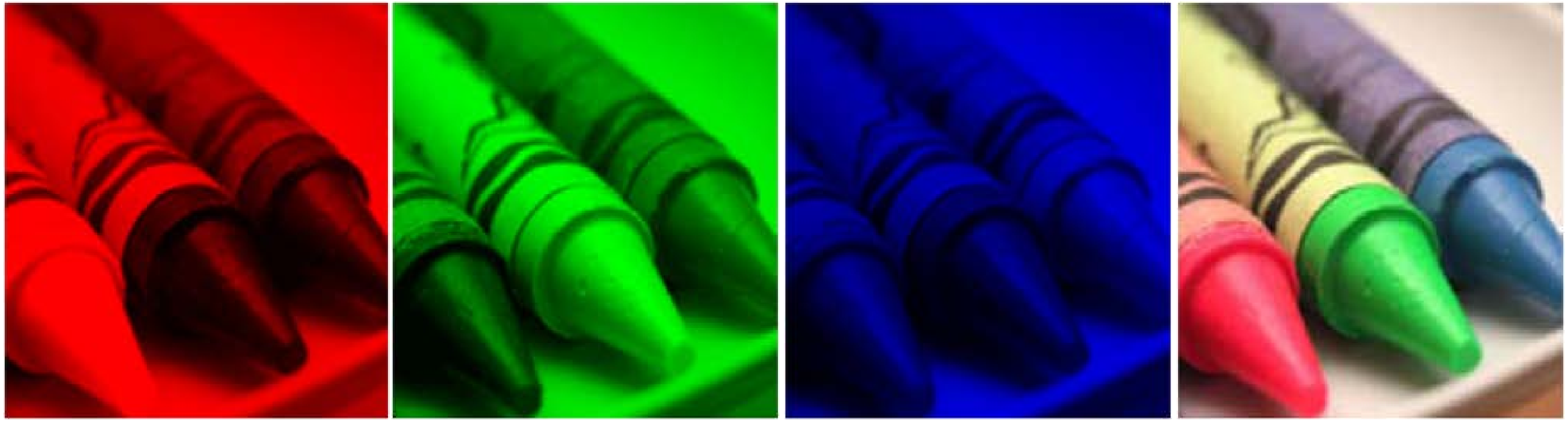






Foveon X3 Sensor

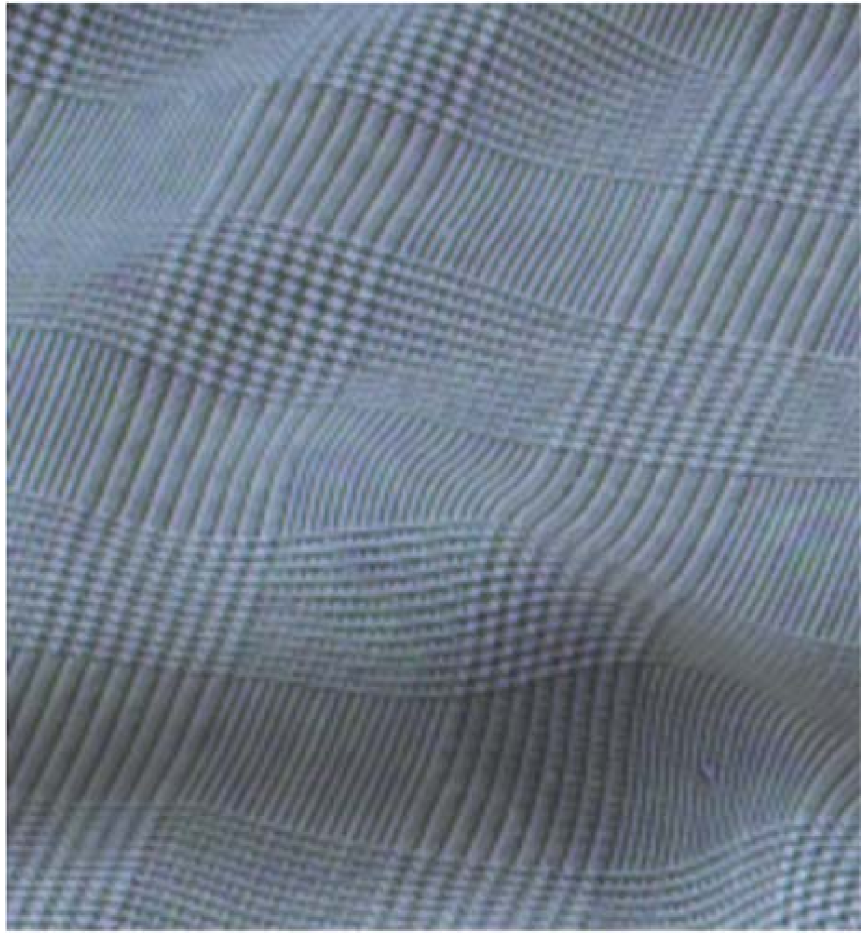




red green blue output

Foveon X3 Sensor

Bayer CFA



X3 sensor

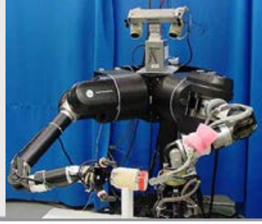
Cameras with Foveon X3 Sensor

Sigma SD10, SD9

Polaroid X530

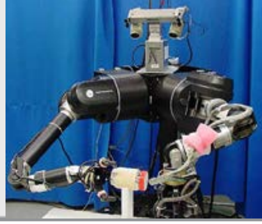
Problems with Real Cameras

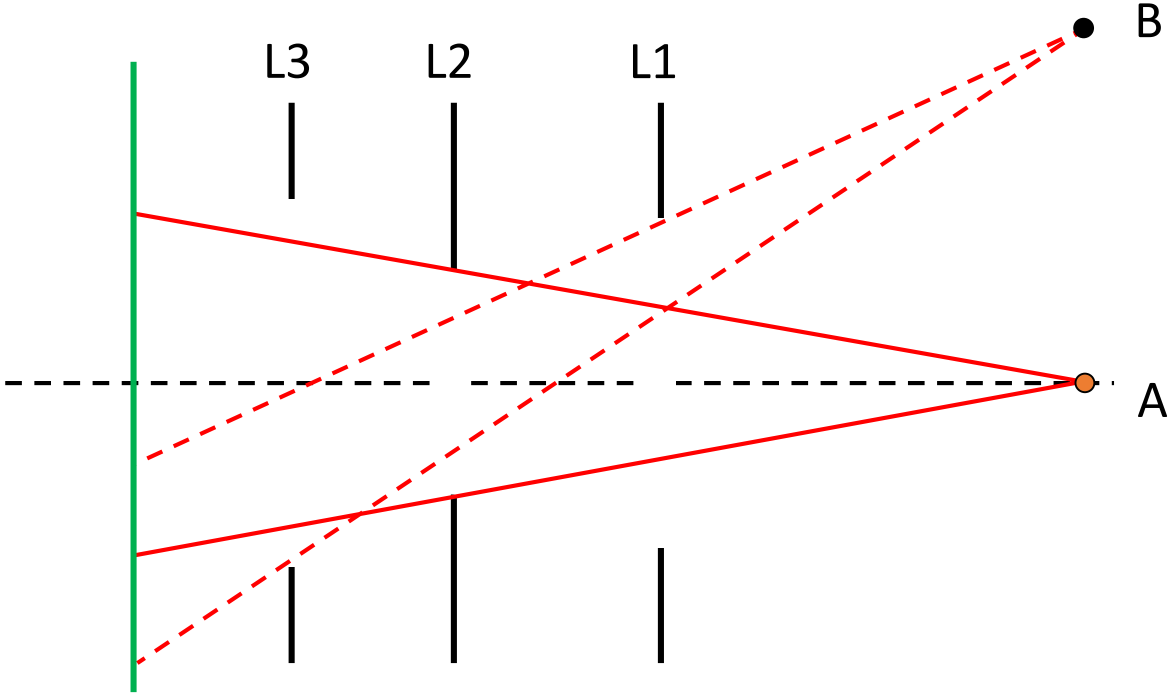
Lens Glare

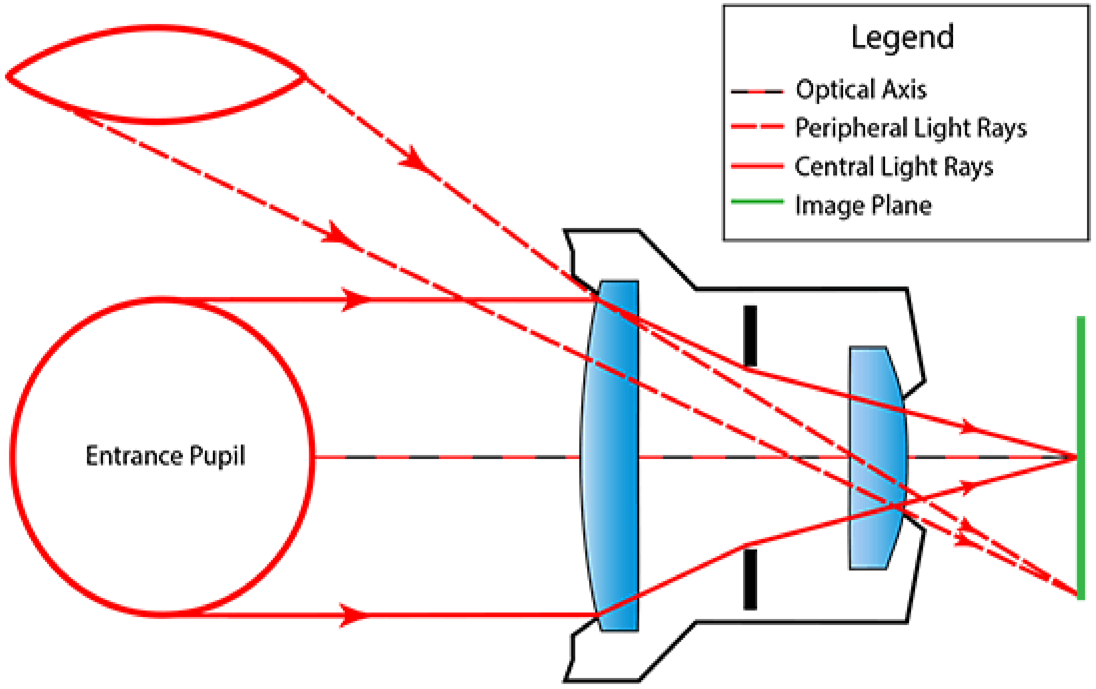


- Stray inter-reflections of light within the optical lens system.
- Happens when very bright sources are present in the scene.

Vignetting





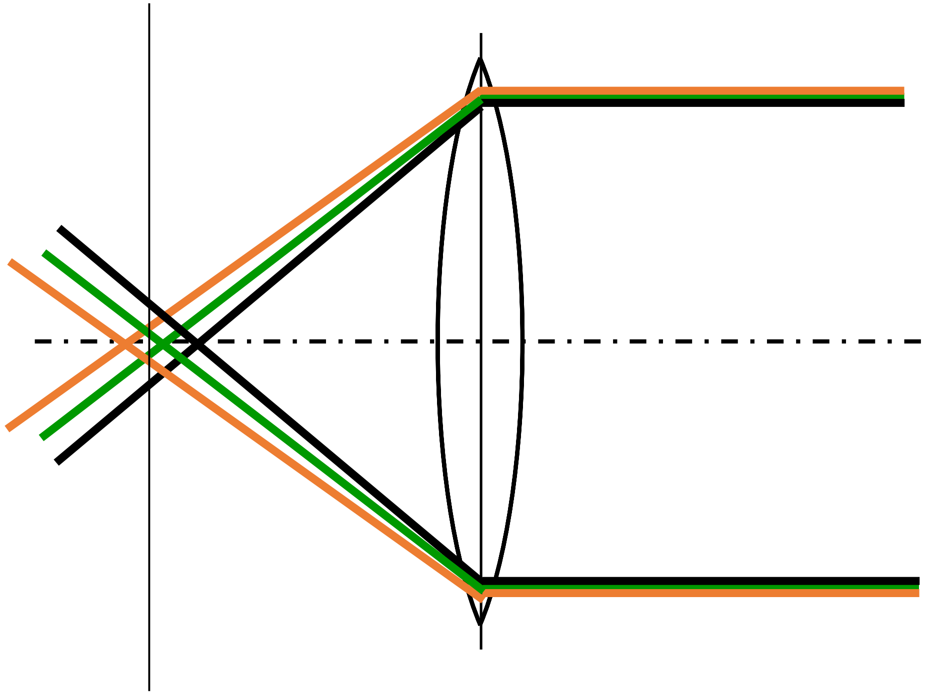


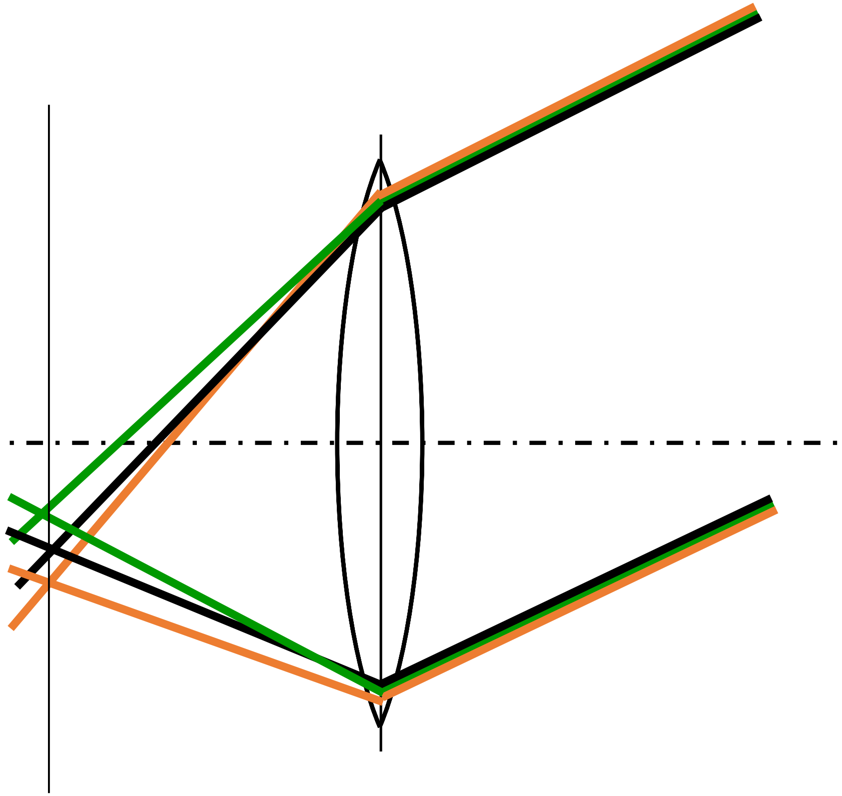
- More light passes through lens L3 for scene point A than scene point B
- Results in spatially non-uniform brightness (in the periphery of the image)

Vignetting

photo by Robert Johnes

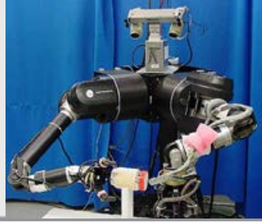
Chromatic Aberration



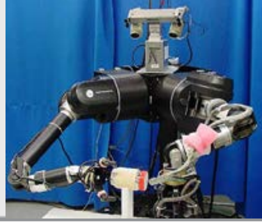


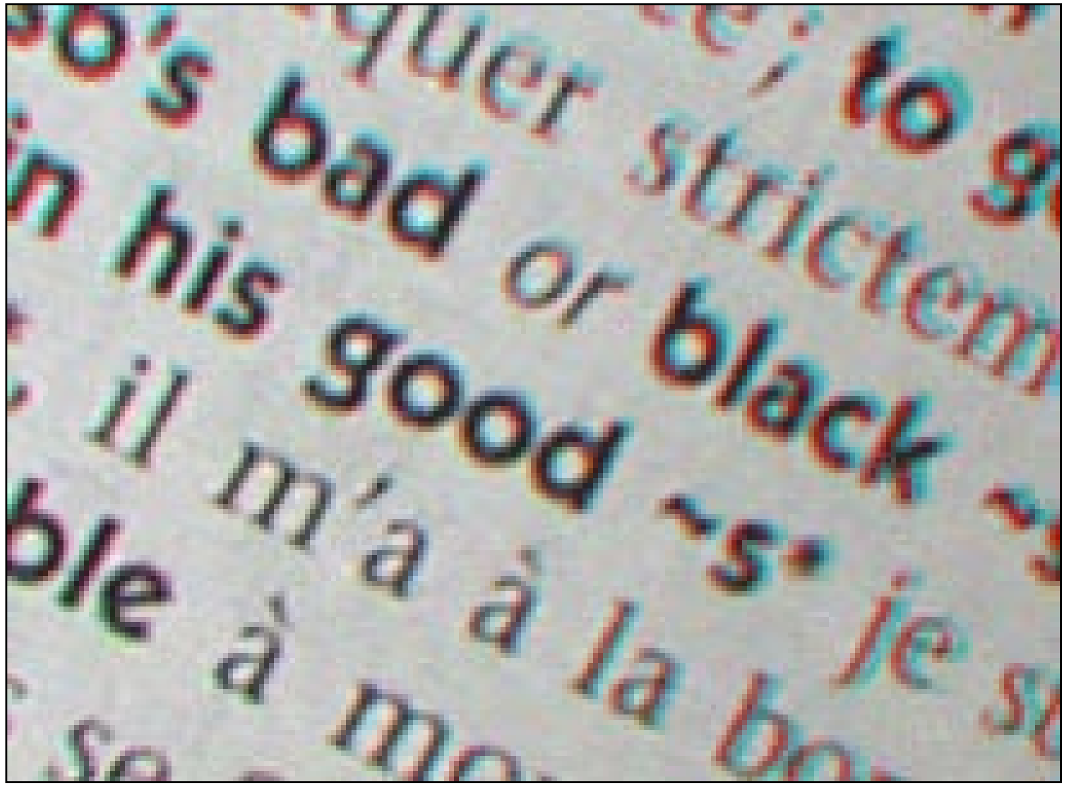
longitudinal chromatic aberration (axial)

transverse chromatic aberration (lateral)



Chromatic Aberration

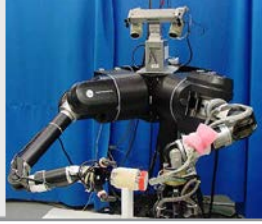




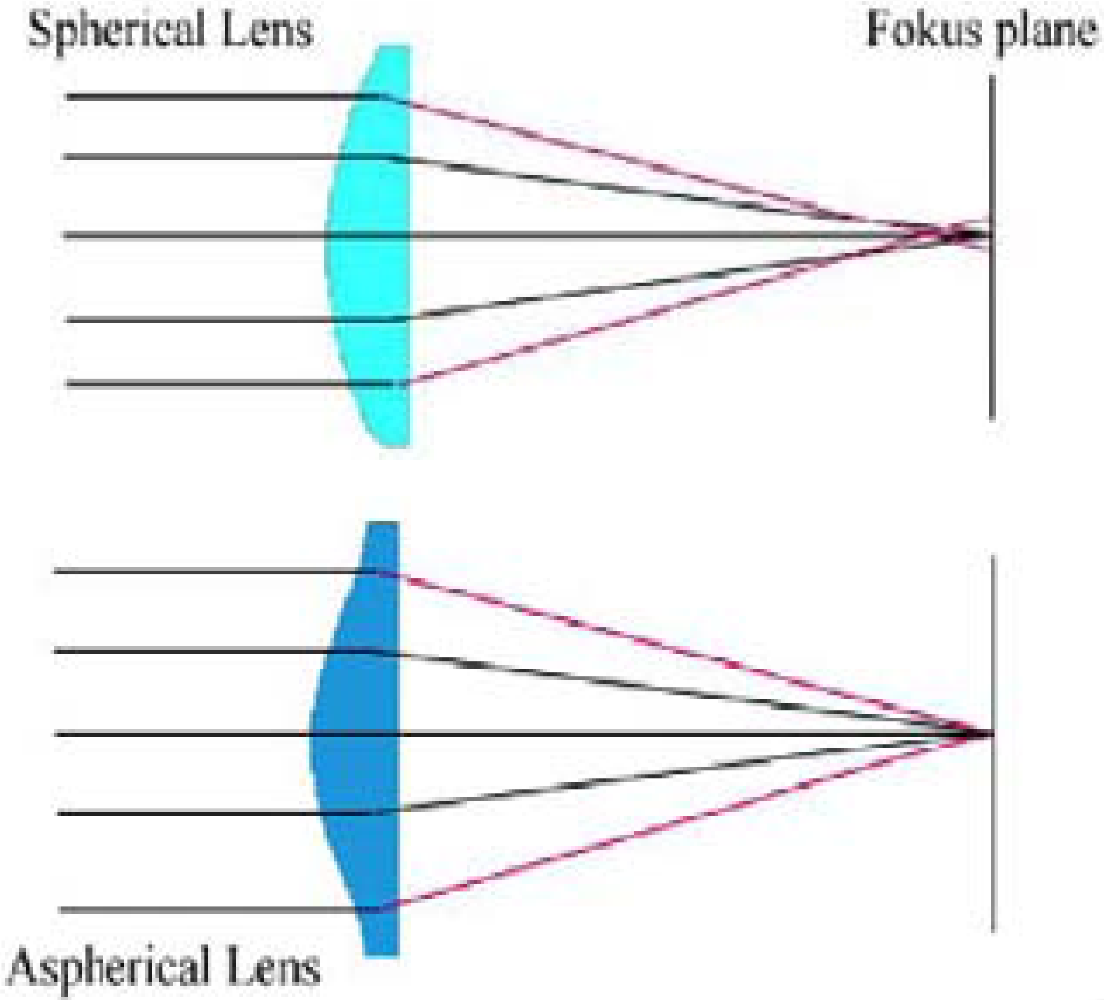
longitudinal chromatic aberration
(axial)

transverse chromatic aberration
(lateral)

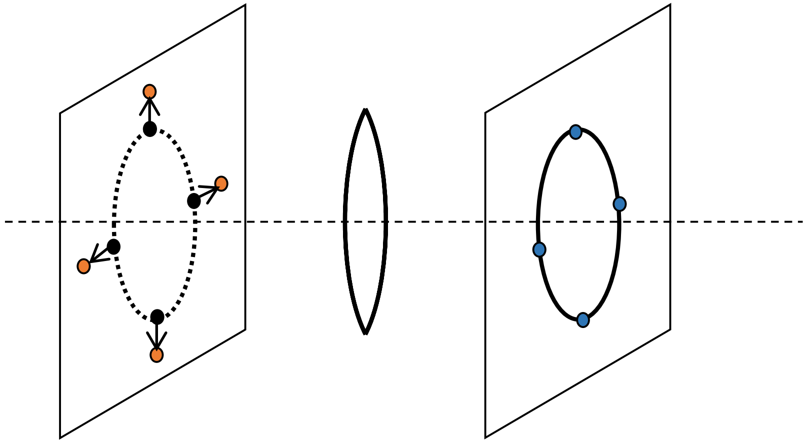
Spherical Aberration



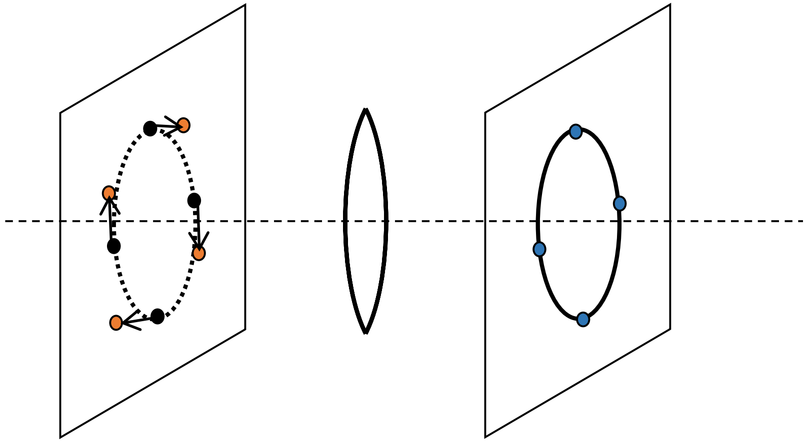
- Effect: sharp image superimposed by a blurred one
- Caused by spherical lens surfaces (manufacturing)
- Parallel rays are focused in one point only if they are close to the optical axis
- Can be avoided by using aspherical lenses with parabolic surfaces



Geometric Lens Distortions



Radial distortion

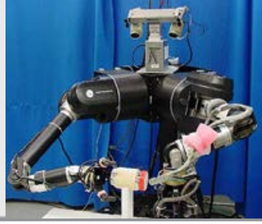


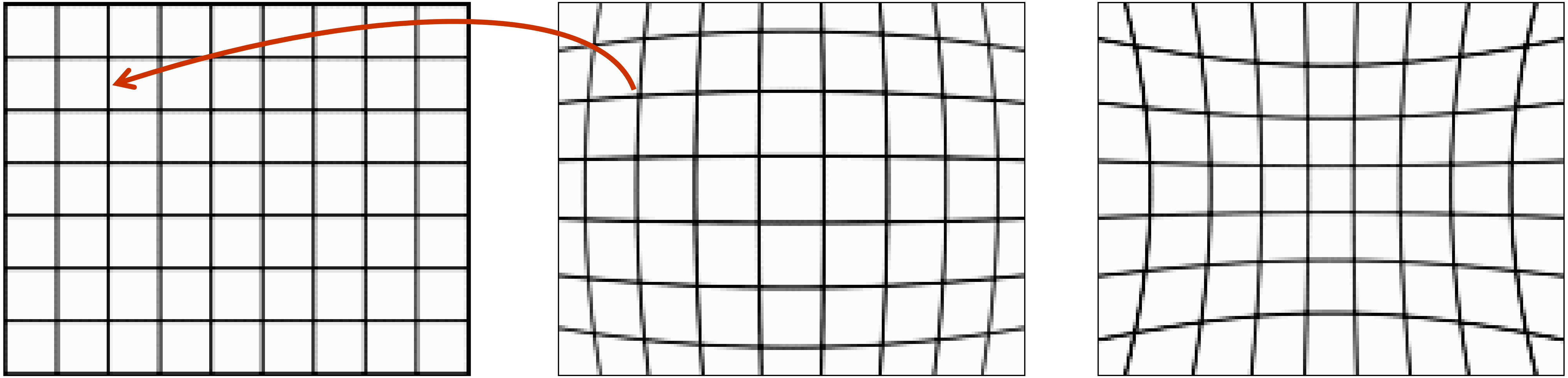
Tangential distortion

Photo by Helmut Dersch

Both due to lens imperfection

Radial Lens Distortions





No Distortion

Barrel Distortion

Pincushion Distortion

- Radial distance from Image Center: $r_u = r_d + k_1 r_d^3$